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CHICAGO

LESSON VII : : : : : TRANSFORMERS

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INTRODUCTION.

As the transformer, more than any other one piece of apparatus, is responsible for the very extensive use of the alternating current system, and because it is so widely used in all branches of electrical work, the student should be very familiar with the principles of its operation and construction.

NATIONAL ELECTRIC LIGHT ASSOCIATION
COURSE IN PRACTICAL ELECTRICITY

LESSON VII—TRANSFORMERS

The Transformer. The alternating-current transformer is a stationary device used to raise or lower the voltage of an alternating-current circuit.

Principle of Induction. If a permanent magnet is thrust into or drawn out of a coil, as represented in Figure I, the turns of the coil are cut by lines of force and a voltage is induced in the coil.

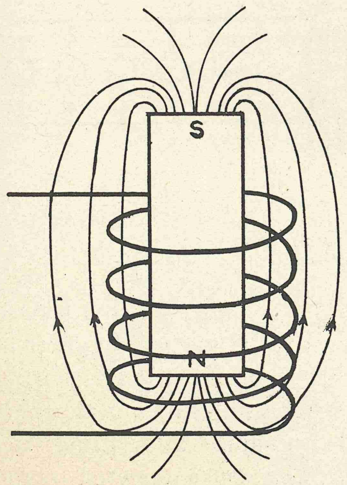


Figure 1—A Permanent Magnet Thrust into a Coil

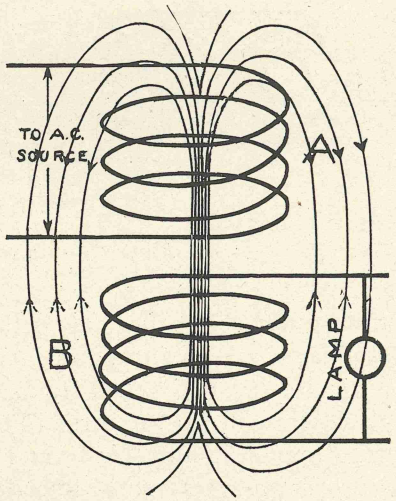


Figure 2—Two Coils A and B, A used as Primary, B used as Secondary

In a similar manner, if two coils are placed so that the lines of force set up by one coil will pass through the other, as in Figure 2, then an electro-motive-force will be induced in the second coil whenever the magnetism passing through it changes in value.

If an alternating current is passed through one of the coils, then the change of magnetism is continuous and the voltage induced in the second coil is also continuous.

Simple Transformer. If the two coils are wound on an iron ring, the coils being entirely insulated from each other and from the iron ring, we have a simple transformer. The only connection between the two coils is magnetic; that is, both coils are wound on the same iron core, so that magnetism set up by one coil will pass through the other.

The purpose of the iron ring is to provide a good magnetic circuit connecting the coils.

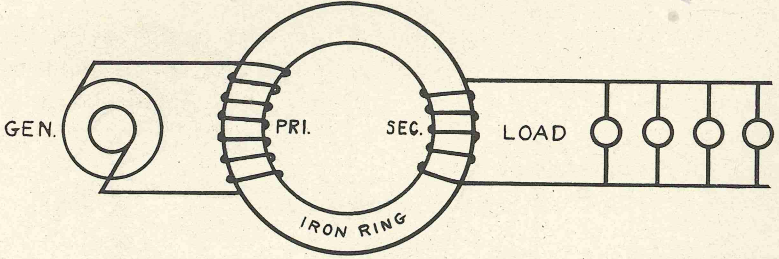


Figure 3—Simple Transformer

Primary and Secondary. If either one of the coils is connected to a source of alternating current, alternating magnetism will be set up in the iron core. This alternating magnetism will cut the turns of the other coil, inducing alternating voltage in it, and this second coil can supply alternating current to lamps, motors, or other load. The coil connected to the source of current is the **Primary** and the coil connected to the load is the **Secondary.** The action of the transformer is reversible; that is, either coil can be used as primary or secondary.

On account of the fact that most transformers on distribution systems are used to change the alternating current from a high voltage supply to a low voltage for lamps, it has become common practice to call the high voltage coil of the transformer primary, and the low voltage secondary. It should be kept in mind that this designation of primary and secondary is not always correct. Transformers used to lower the voltage are called step-down transformers, and transformers used to raise the voltage are called step-up transformers.

Voltage Relations. If the two coils on the ring described have the same number of turns of wire and if all of the magnetism set up by the primary passes through the secondary, then the secondary will deliver the same voltage as that delivered to the primary.

If the secondary coil has one-half as many turns as the primary, then the voltage induced in it will be half as great as that supplied to the primary. In other words, the relation of the voltage of the primary coil to the voltage of the secondary coil is the same as the relation between the turns of wire on the two coils. Expressed as a ratio:

$$E_p : E_s :: N_p : N_s.$$

Where E_p is the voltage supplied to primary.
E_s is the voltage delivered by secondary.
N_p is the number of primary turns.
N_s is the number of secondary turns.

Thus, if a transformer has a primary coil of 2,000 turns and a secondary of 200, and the primary is connected to 2,000 volts, the secondary will deliver 200 volts. This relation can be reversed and 200 volts supplied to the low voltage coil as a primary, and the other coil will deliver 2,000 volts.

The voltage induced in the secondary of a transformer depends upon the rate of cutting lines of force. That is, the voltage depends upon the number of turns of wire, the quantity of magnetism, and the rate at which the magnetism changes.

Transformers are designed and constructed for all voltages, from the very lowest of a few volts for doorbell and buzzer work, to 220,000 volts for our highest voltage transmission systems. Transformers for experimental work have been built for voltages as high as 1,000,000.

Current Relations. The current relations of primary and secondary are in inverse ratio of the turns. If high voltage and low current are supplied to the primary and the secondary delivers a lower voltage, then the secondary current is proportionally larger. That is to say that the watts output of the secondary is almost equal to the watts input of the primary. Therefore, if the voltage of one coil is high, its current will be proportionally low, or, if the voltage is low, the current will be high.

Thus, if the transformer just mentioned delivered 100 amperes at 200 volts, then the primary would be taking a little over 10 amperes at 2,000 volts.

Change of Current With Load. The transformer, like the motor, is self-regulating; that is, the input is automatically determined by the output demanded from it. In the case of the motor we saw how this depends upon the counter electro-motive-force induced in the armature. There is much the same thing in the transformer, but here the counter-electro-motive-force is that of self-induction in the primary.

If the secondary of a transformer is open, that is, it is delivering no current, then the primary is simply a coil of many turns on an iron core and offers high inductance. The primary then takes a very small current at very low power-factor; in fact, the current is then lagging almost 90 degrees behind the voltage. If the secondary delivers current, its magnetic effect opposes that of the primary; the inductance of the primary is, therefore, slightly less because there is less magnetism, and the primary takes a larger current. The power factor of the load supplied by the transformer determines the power factor of the transformer. If a transformer secondary is fully loaded, with incandescent lamps or other non-inductive load, then the power factor of the transformer is high, being almost unity.

Transformer Losses. In all transformation of power some power is lost, and this loss appears as heat. In the transformer the losses are the following:

I^2R losses in primary and secondary. (Due to resistance of wire).
Iron losses.

As explained in Lesson II, whenever current flows in a conductor there is a loss due to the resistance of the conductor, and this loss is equal to the square of the current (I^2) multiplied by the resistance (R).

Whenever magnetism changes in an iron core two losses take place, namely, **Hysteresis loss and Eddy Current loss.** It will be remembered that hysteresis loss is produced by reversal of magnetism, i. e., friction between the molecules as the magnetism reverses, and that the eddy current loss is due to the fact that electric currents, called local or eddy currents, are set up in the iron of the core, and produce heat.

The hysteresis loss is reduced by the use of iron of high magnetic quality. The eddy current loss is reduced by laminating the core; that is, making up the core of sheet steel or punchings, continuous in the direction of the lines of force but separated in the direction in which the eddy currents would flow, thus offering a high resistance to the flow of eddy currents.

The copper losses occur only when current is flowing in the coils; that is, at time of load. The iron losses are practically constant and occur whether there is a load on the transformer or not, if the primary is connected to the mains. The power loss in this way, 24 hours per day, every day in the year, is quite an item.

Transformer Efficiency. Here, again, the **efficiency is** expressed as **the ratio of Output** to **Input.** That is:

$$\text{Transformer Efficiency} = \frac{\text{Watts Output}}{\text{Watts Input}}$$

The transformer is a very efficient piece of apparatus and at full load the efficiency of a large transformer may be as high as 99 per cent. At very light loads the efficiency is of course low.

The point of highest efficiency is the point at which the watts iron loss equals the watts copper loss This can be controlled by the designer and is varied according to whether a transformer is to run at full load most of the time, as would a power transformer, or be run at light load or at no load most of the time, as would a transformer used for residence lighting. A power transformer is designed to give its maximum efficiency at full load, or above, while a lighting transformer is designed to give its highest efficiency below full load. This means the best efficiency for both over a 24-hour period, or what is called, **all-day efficiency.**

$$\text{All-day Efficiency} = \frac{\text{Watt-hours output in 24 hrs.}}{\text{Watt-hours input in 24 hrs.}}$$

This, of course, is low if the transformer delivers power for only a small part of the 24 hours.

Transformer Rating. Transformers, like alternating current generators, are rated in kilovolt-amperes output instead of kilowatts, and for the same reason; that is, the transformer is fully loaded when it is delivering full load current and voltage even at low power-factor and has a comparatively low actual kilowatt output.

Transformers are usually designed to carry 25 per cent overload continuously and 50 per cent overload for a few hours.

Transformer Construction. Figure 4 gives a good idea of the mechanical arrangement of the parts of a transformer. The iron core is built up of sheet steel laminations parallel to the plane of the paper. Each lamination is divided as indicated on the dotted lines, in order that the coils can be machine wound and the laminations assembled about the coils. The laminations are of high grade transformer steel and each lamination is usually about 0.015 of an inch in thickness.

The coils are form-wound and usually alternated, as in the figure; that is, the primary and secondary are each made up of a number of coils interlaced as shown, so that there is as little magnetic leakage as possible. This means that almost all of the magnetism that is set up by the primary passes through the secondary coils. The primary and secondary coils are very well insulated from each other and from the iron core.

Terminals of the coils are usually brought out to a porcelain terminal block, although some manufacturers are making transformers without terminal blocks to meet the demand of engineers who are convinced that terminal blocks cause much trouble in transformers.

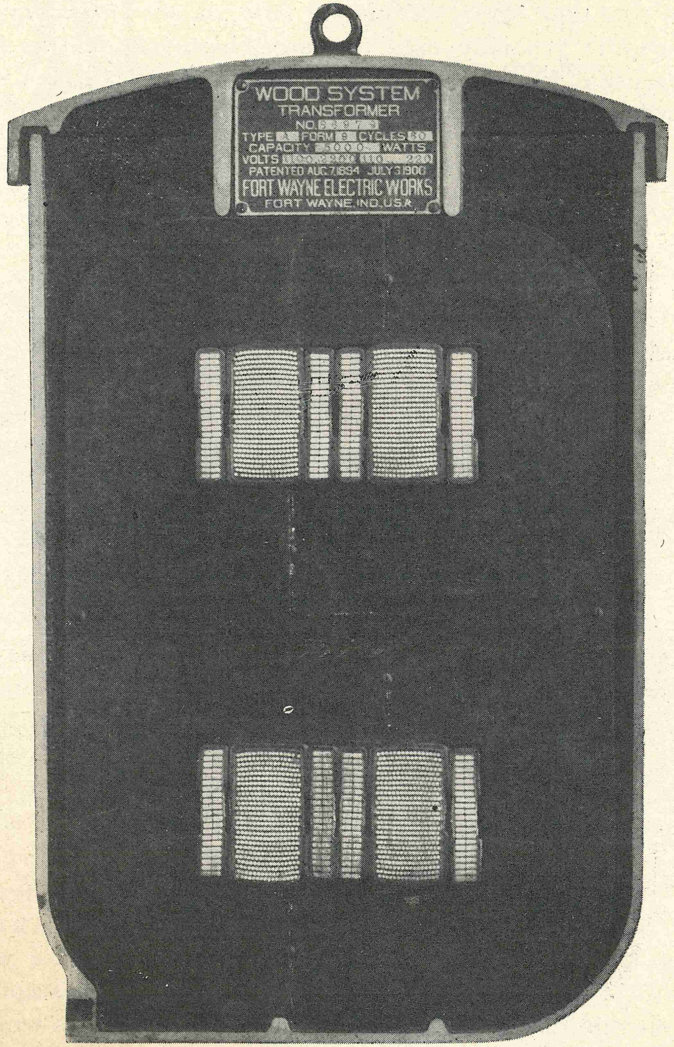


Figure 4—Cross-Section of a Shell-Type Transformer, Showing Laminations, and Sections of Primary and Secondary Coils

Classification According to Type of Core. Transformers are often classified according to the shape of the core used, as:

Core-type.
Shell-type.
Cruciform-type.

The **core-type** has a rectangular core, as shown in Figure 5 and is quite generally used for large, high-voltage transformers because of its simplicity and because of the small floor space required.

The **shell-type** is also illustrated in figure 6. In this the coils are almost completely surrounded by iron.

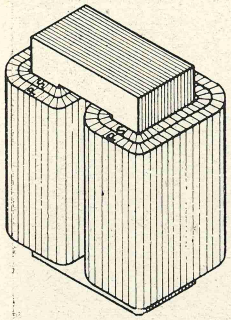


Figure 5—Sketch of Core-Type Transformer

The **cruciform-type** is a modification of the shell-type as shown in Figure 7 and has the advantage of presenting more cooling surface to the oil than does the shell-type.

All of these types are in common use and there is little advantage of one over another except from the manufacturing point of view. The cruciform is the latest type.

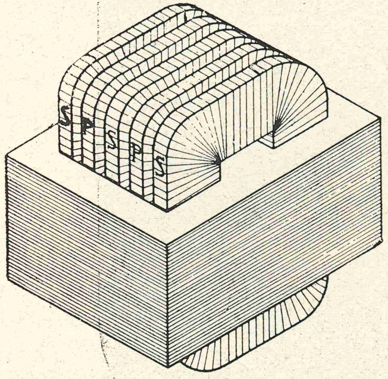


Figure 6—Sketch of Shell-Type Transformer

Transformer Connections. Transformers are usually made with the primary and secondary both divided so as to get several voltage combinations with the same transformer. Generally the primary is made in two parts as shown in Figure 8 so that, with the two halves in parallel, the transformer can be used on 1,150 volts or with the halves in series on 2,300 volts. The secondary can be connected with coils in parallel for 115 volts or in series for 230 or with the last connection a third wire will give a three-wire secondary, supplying both 115 and 230 volts.

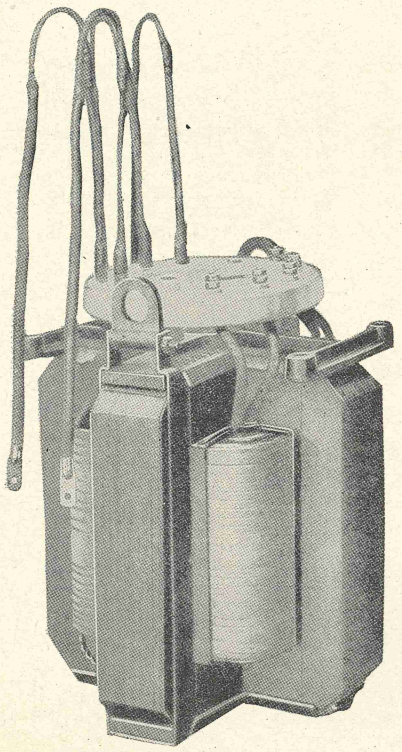


Figure 7—Cruciform Type of Transformer

Methods of Cooling. The first transformers were of the type known as dry, which had an air space between transformer and case and had an opening in the lower part of the case to allow for ventilation. It was found that the insulation of these transformers did not stand up very well. It absorbed moisture or would become exceedingly dry, and the transformer was easily overheated because the heat was not taken away rapidly. The type was soon replaced by other more improved types.

The methods of cooling now in common use are the following:

Oil insulated, self-cooled.
Oil insulated, water-cooled.
Air Blast.

Oil-Insulated Self-Cooled. The oil insulated, self-cooled transformer has a space between the transformer core and coils, and the case filled with what is called transformer oil. This oil is a special high flashing point oil, free from moisture, and has high insulating properties. The transformers are constructed so that there are a number of ducts through the core and between the coils, through which the oil can circulate.

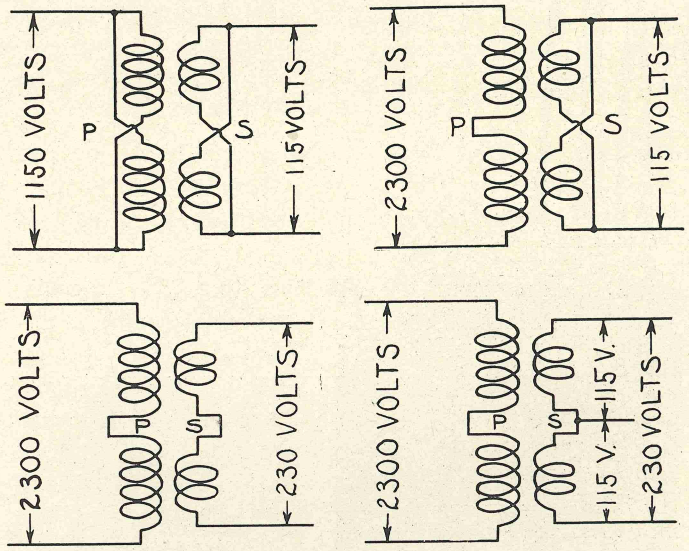


Figure 8—Some Voltage Combinations.

The oil preserves the insulation of the transformer, is an excellent insulator itself and serves to carry the heat from all parts of the core and coils to the case which delivers the heat to the surrounding air. There is an actual circulation of oil in the case, the cooler oil settling to the bottom of the case and the hotter, lighter oil rising to the top. This method of cooling is used on all outdoor types of transformers and is very satisfactory.

This type of transformer is extensively used in substations, and the present practice is to provide large external radiators, in order to increase the radiating surface.

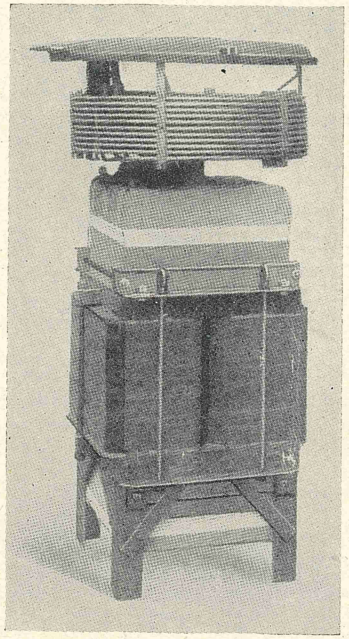


Figure 9—Typical 1500-Kva. Shell-Type Oil Insulated Water Cooled Transformer Removed from Tank—Westinghouse Co.

Oil-Insulated Water-Cooled. In this type of transformer, a coil of pipes is installed in the upper part of the oil space. Cooling water is passed through these pipes, thus taking the heat from the hottest oil in the transformer and improving the oil circulation. Figure 9 shows a water-cooled transformer.

This method is very commonly used in electric stations and substations.

Air-Blast. Transformers of this type are constructed so that air can be blown up through the transformer. They are usually installed over an air chamber, a blower maintaining the air pressure in the chamber.

This method is also commonly used in stations and substations.

Comparison of Methods of Cooling.

The **oil-insulated,** self-cooled, transformer is the most expensive as to first cost, as it must be the most generously designed; that is, it has the most material in it for a given capacity. It, therefore, occupies the greatest space. It has the decided advantage, however, of requiring the least attention and is the least expensive to operate.

The **water-cooled** transformer costs less for a given capacity, as it is smaller, but requires a water-cooling system which is expensive to install and operate.

The **air-blast** is the least expensive as to first cost, but most expensive as to operating costs, as a motor-driven blower must be in operation all of the time the transformer is in use.

Water-cooled and air-blast transformers are installed only where an operator is in attendance at all times.

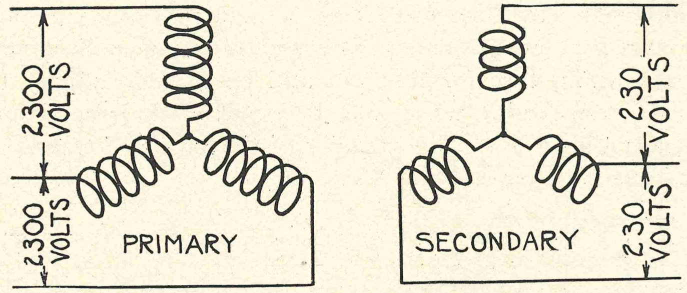
Oil-insulated, self-cooled transformers are always used in substations having no regular operators.

Indoor and Outdoor Types.

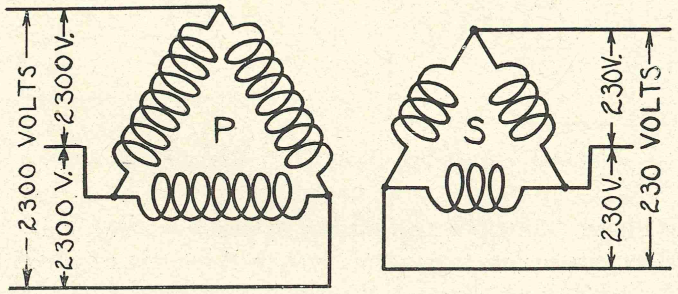
Large transformers have slightly different constructions, according to whether they are to be used indoors or outdoors. The difference in construction is primarily in the covers of the cases. For outdoor use the leads are brought out through water-tight insulators, and the covers are waterproof, while for indoor use the leads are brought out through porcelain bushings, often through wooden **covers.**

Three-Phase Transformation.

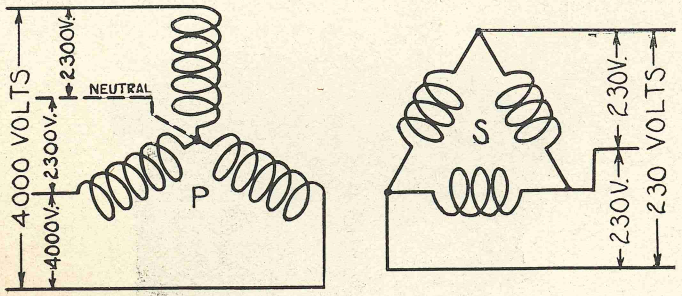
For transforming three-phase currents, either single-phase or polyphase transformers may be used. Single-phase transformers are most commonly used, connected according to one of the combinations of Figure 10, with desired voltage ratio. Just which combination is used, depends upon the system to which the transformers are connected.



Star Primary Star Secondary



Delta Primary Delta Secondary



Star Primary (Four Wire.) Delta Secondary

Figure 10—Connections of Single-Phase Transformers on Three-Phase System, Assuming 10:1 Ratio of Coils.

Delta-connected primaries and secondaries give the advantage, that if one transformer is burned out or open circuited, the two remaining transformers can still be used to supply three-phase current, with what is called **open-delta** connection, as shown in Figure 11. The capacity of the group of transformers is of course reduced.

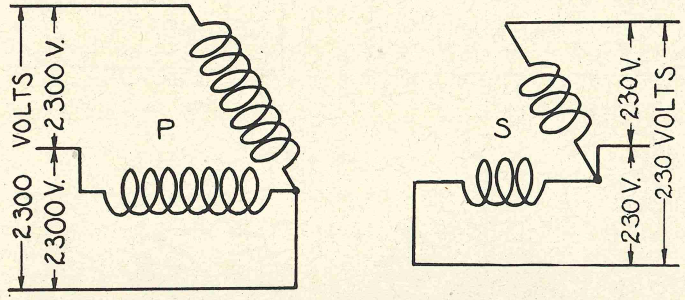


Figure 11—An Open-Delta Three-Phase Connection

Three-Phase Transformers. Single transformers so designed and constructed as to transform two or three phase current are quite generally used. Figure 12 shows a transformer of this kind for three-phase service. As will be seen, it has three cores and three sets of coils, one set for each phase.

Such transformers are little used for general distribution work, largely because, in small sizes, they cost more than the same capacity in single-phase transformers and are much less flexible in their use.

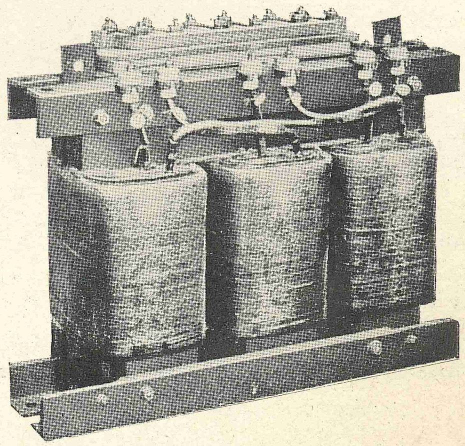


Figure 12—A Three-Phase Transformer—Case Removed —General Electric Co.

Polyphase transformers are, however, quite generally used, in the large sizes, for stations, substations, and large power customers. In the larger sizes the cost is less, weight is less, and space occupied less than for single-phase transformers of the same total capacity. There are offsetting disadvantages, such as greater cost of repairs and spare parts, longer interruption to service in case of breakdown, and less overload capacity when self-cooled.

Two-Phase to Three-Phase Transformation. It is often desirable, to transform from two-phase to three-phase, or vice versa. This is most easily done by what is called the Scott system. Two transformers are used, and are connected as shown in Figure 13. To transform from two to three-phase, the primaries of the two transformers are connected to the two-phase mains, in the same manner as for regular two-phase service. One of the transformers has a special connection brought out from its secondary, such that 86.6 per cent of the winding is included between one end of the secondary and this tap. Connecting either the tap, or the end of the coil, to the center of the secondary of the other transformer, three lines can be brought out, as shown in the figure, having regular

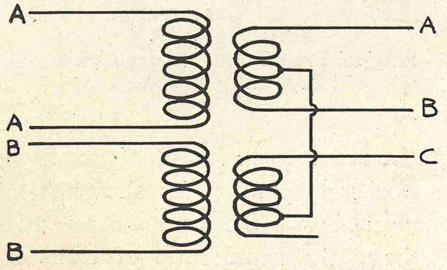


Figure 13—Two-Phase to Three-Phase Transformation

three-phase relations between them. With the same connections, power can be transformed from three-phase to two-phase, by simply supplying power to the three-phase side.

Transformer Grouping. Early practice in the use of transformers was to have a separate transformer for each customer as shown in Figure 14. This meant a large number of small transformers, with corresponding large losses and low efficiency. Later, fewer transformers were used, operating in groups connected in parallel. The present practice for lighting service is to use single, large transformers to supply a block or a large number of customers. This, of course, means lower first cost, lower losses, and higher efficiency for the system.

For large power service, each customer has a separate bank of transformers.

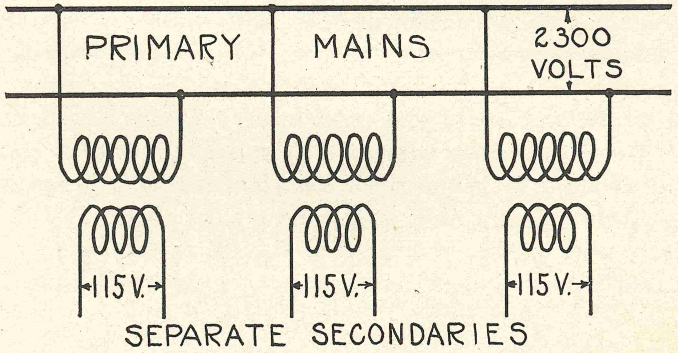

PRIMARY
MAINS
2300 VOLTS
115 V.
115 V.
115 V.
SEPARATE SECONDARIES

Figure 14—Single-Phase Transformers Connected to Supply Separate Customers

Parallel Operation of Transformers. In order to have transformers operate satisfactorily in parallel, as shown in Figure 15, they must be for the same voltage and frequency and have the same ratio of transformation. They must also have their reactances inversely proportional to their capacities.

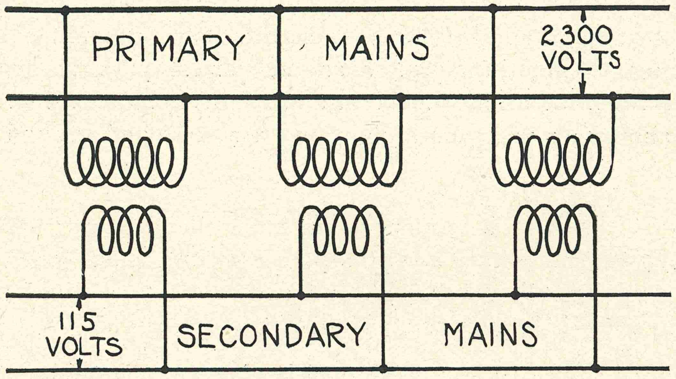

PRIMARY
MAINS
2300 VOLTS
115 VOLTS
SECONDARY
MAINS

Figure 15—Single-Phase Transformers in Parallel

Protecting Transformers. Transformers must be protected against excessive over-load by proper fuses on the primary side. They should also be protected against damage from lightning, by the use of some good lightning

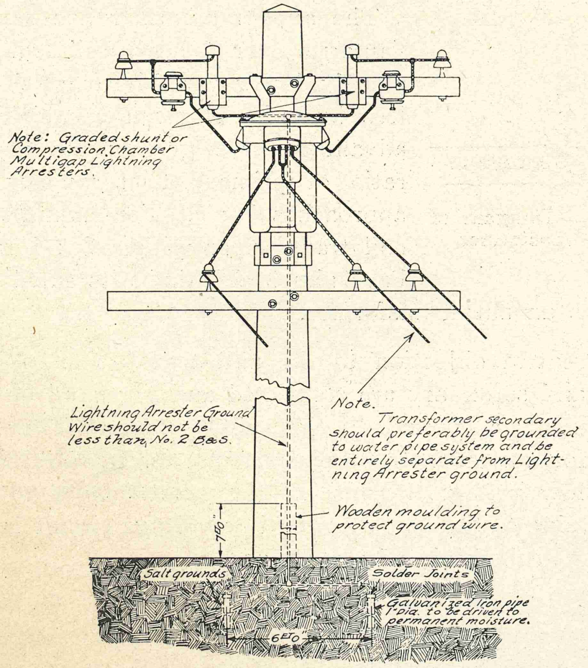

Note: Graded shunt or Compression Chamber Multigap Lightning Arresters.
Lightning Arrester Ground Wire should not be less than No. 2 B.&S.
Note. Transformer secondary should preferably be grounded to water pipe system and be entirely separate from Lightning Arrester ground.
Wooden moulding to protect ground wire.
7'0"
Salt grounds
Solder Joints
Galvanized iron pipe 1" dia. to be driven to permanent moisture.
6'0"

Figure 16—Sketch of Distribution Transformer with Primary Fuses and Lightning Arresters*

arrester. Transformers on distributing lines are more likely to be damaged by lightning, because the distributing lines carry lightning to the transformers as the easiest path to ground. Figure 16 shows an arrangement and connections of a distributing transformer with fuses, lightning arresters and ground.

---

*General Electric Co.

Auto-Transformers. Most transformers have the primary and secondary as two separate sets of coils. They can, however, be combined to form a single coil, making what is known as an **Auto-Transformer.**

Figure 17 represents a single coil having a tap brought out so as to give a secondary voltage of about one-fourth of the primary voltage. The total voltage delivered to the coil is equally divided between the turns of the coil, so that the voltage between the secondary taps holds the same relation to the total voltage that the number of turns between the secondary taps holds to the total number of turns on the coil.

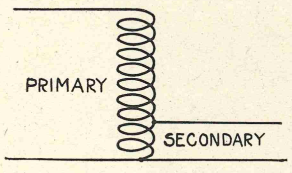


Figure 17—Diagram of Auto-Transformer

The auto-transformer has several advantages over the two-coil transformer: namely, lower cost, higher efficiency, and less bulk for a given capacity. These advantages are greater the nearer the ratio of primary to secondary voltage approaches 1 : 1. For example, a two-coil transformer with a 2 : 1 ratio will have almost 2.5 times its rated capacity if used as an auto-transformer.

The greatest objection to the auto-transformer is that the primary and secondary are connected and a ground on the secondary means a ground on the supply mains. They are not suitable for use on distribution systems, for transforming from high to low voltage, because of the great danger to life and property, due to the fact that the low voltage circuit is directly connected to the high voltage mains.

Auto-transformers are very generally used for supplying low voltage to motors for starting. They are quite generally used for supplying 110 volt lights from 220 to 550-volt mains. A three-wire auto-transformer, or balance coil as it is sometimes called, is shown in Figure 18.

If the primary voltage on this was 460, the secondary voltages would be 115 and 230. Auto transformers are sometimes used in generating stations to raise the generator voltage to a higher value for transmission as from 11,000 volts, generator voltage, to 22,000 transmission line voltage.

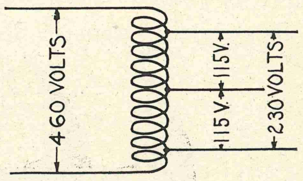


Figure 18—Auto-Transformer to Supply Three-Wire Service

Constant-Current Transformers. The transformers so far considered are of the **constant voltage** class, in as much, as they supply practically a constant voltage and the amount of current required by the load.

There is another class of transformers called **constant-current transformers.** These supply a given amount of current, at whatever voltage is required by the load. This class of transformers is used principally for series street lighting, where all of the lights are connected in series and receive the same current. The voltage supplied by the constant-current transformer depends upon the number of lamps in the circuit, and changes automatically as the number of lamps changes. A constant-current transformer will give the same current from a short circuit, which requires practically no voltage, to the full number of lamps in series, which may require 7,500 volts.

This regulation of voltage is not as simple as the regulation of current in a constant voltage transformer, and requires a special transformer.

The constant-current transformer consists of two coils, one stationary and one movable, mounted on an iron core as shown in Figure 19. The lower coil is the stationary and the upper, the movable coil. The movable coil is supported from one end of a lever counter-balanced by a weight. The lower coil is the primary and the movable coil is the secondary. The closer the secondary coil is to the primary, the more lines of force will cut it and the higher the voltage that will be induced in it.

The current induced in the secondary is opposite to that flowing in the primary. It will be remembered that conductors carrying current in opposite directions repel each other and there is therefore always a repelling force, between these two coils, when current is flowing in both. The counter-balancing weight can be so adjusted that the secondary current will remain the same for all values of load. If the resistance of the circuit decreases, then the current increases, the repelling force increases, and the secondary coil moves farther away from the primary until the current decreases to the given value. If the resistance of the circuit increases, the current decreases, the repelling force decreases and the secondary coil moves closer to the primary until the current increases to the given value.

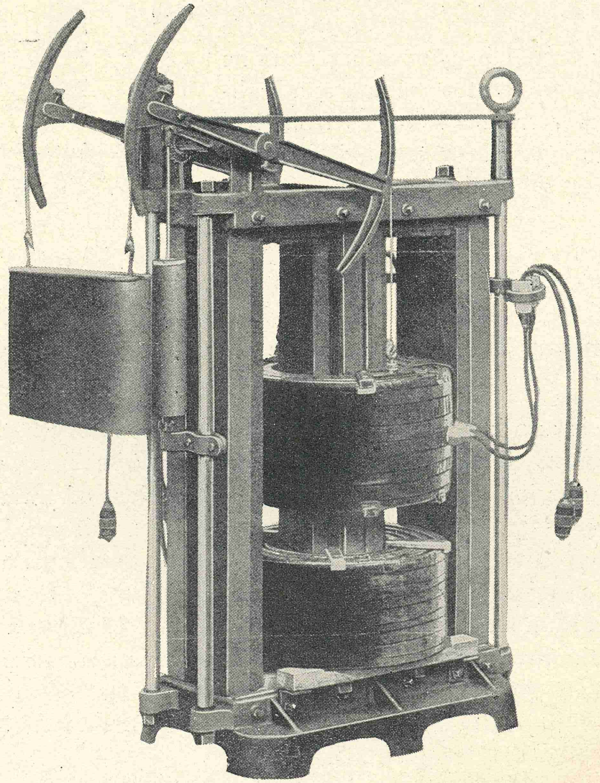


Figure 19—Constant-Current Transformer—General Electric Co.

Constant-current transformers are usually operated so as to supply any desired current from 5 to 10 amperes.

DEMONSTRATION FOR LESSON VII.

1. If possible have small transformers of core-type, shell-type, and cruciform-type open for inspection.

2. Visit an a. c. substation in order to show transformer installations and methods of cooling transformers.

3. Also visit a substation having constant-current transformers.

REFERENCE BOOKS.

Electricity Experimentally and Practically Applied, by Sidney W. Ashe, D. Van Nostrand Co., New York.

Applied Electricity for Practical Men, by Arthur J. Rowland, McGraw-Hill Book Co., New York.

Elements of Electricity and Magnetism, by Franklin and McNutt, McMillan Co., New York.

Elements of Electricity, by Timbie, McMillan Co., New York.

Elements of Electricity and Magnetism, by D. C. and Wm. B. Jackson, McMillan Co., New York.

Continuous and Alternating Current Machinery, by J. H. Morecroft, John Wiley & Sons, New York.

Alternating Currents, by George T. Hanchett, John Wiley & Sons, New York.

The Alternating Current Transformer, by F. G. Baum, McGraw-Hill Pub. Co., New York.

The Principles of the Transformer, by Frederic Bedell, McMillan Pub. Co., New York.

Transformer Practice, by W. T. Taylor, McGraw-Hill Pub. Co., New York.

QUESTIONS.

Note: These questions are to be answered after the lesson has been studied carefully, and without further reference to the lesson.

1. Explain fully the simple theory of the transformer.
2. Describe briefly the arrangement of parts in shell and core types of transformers.
3. Discuss briefly the several methods of cooling transformers.
4. What is an auto-transformer?
5. Describe the constant-current transformer.

INDEX.

Page
Auto-Transformers 20
Classification, Types of Cores 10
Connections, Transformer 10
Construction, Transformer 8
Constant-Current Transformers 21
Cooling, Methods of 11
Current, Change of, with Load 6
Current Relations 6
Efficiency, Transformer 7
Grouping, Transformer 18
Induction, Principle of 3
Losses, Transformer 7
Parallel Operation of Transformers 18
Primary and Secondary 4
Protecting Transformers 19
Rating, Transformer 8
Three-Phase Transformation 14
Three-Phase Transformers 16
Two-Phase to Three-Phase Transformation 17
Transformer, Simple 4
Voltage Relations 5

NOTICE.

Special sheets for answers to test questions have been sent to you. These answers should be sent to the Chairman within 30 days. They will be corrected, graded and returned to you direct or through your class leader.

Certificates will be granted to those obtaining an average grade of 70 per cent or over.

These lessons will not be forwarded, therefore any change of address must be reported immediately to the Chairman by separate letter.

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3. Elements of Electricity.
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LESSON VI : ALTERNATING-CURRENT MOTORS

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INTRODUCTION

On account of the fact that alternating-current motors are made in many different types, each especially suited to some particular motor need, the student is likely to think that the subject of alternating-current motors is very difficult. The fundamental principles of operation and construction are, however, comparatively simple, and these should be mastered.

NATIONAL ELECTRIC LIGHT ASSOCIATION
COURSE IN PRACTICAL ELECTRICITY

LESSON VI—ALTERNATING CURRENT MOTORS

Relations Between Generator and Motor. With alternating currents, as with direct currents, we find that the generator is reversible and can be run as a motor. The same identical machine used as an alternating-current generator will run as an alternating-current motor if supplied with alternating current.

In direct currents we found that all of the motors were constructed the same as the generators, but in alternating currents we have many types of motors that are not used as generators; in fact, that could not be used as generators.

Types of Alternating-Current Motors. The principal types of alternating-current motors are the following:

Synchronous motors.
Induction motors.
Repulsion motors.
Series motors.

These will be considered briefly in this lesson.

Synchronous Motor. The synchronous motor is the alternating-current generator reversed. That is, if an a-c. generator has direct current supplied to its field and alternating current supplied to its armature it will run as a motor. If supplied with alternating current of the frequency that it generated, it will run at exactly the same speed as a motor, as when driven as a generator to generate the same frequency. In other words, the speed of a synchronous motor is exactly proportional to the frequency of the supply current and it is an absolutely constant speed motor when supplied from an absolutely constant frequency. This type of motor is little used because of two serious drawbacks; these are that it requires direct current for field excitation and that it must be brought up to speed and synchronized the same as an a-c. generator. These disadvantages have limited its use largely to power plants and sub-stations of electric light companies. In recent years its use has become more general as it is now constructed so as to be more easily started.

Regulation of Power factor by Synchronous Motors. The greatest advantage of the synchronous motor is the fact that it furnishes a means for regulating the power factor of a system. The power factor of a synchronous motor can be adjusted by changing its field current. If the field excitation is low, the synchronous motor takes a lagging current, while if the field excitation is high it takes a leading current. This can be more readily understood by referring to Figure 1, which shows what is called the V curve of a synchronous motor. It will be noted that the alternating-current input into the armature changes as the field current changes, having a minimum value at a certain value of field current, and being greater for other values of field current. In other words, the apparent watts change, the true watts being the same if the load is unchanged. The power factor can thus be changed over a wide range, from a large lag to a large lead. Unity power factor is obtained when the field current is so adjusted as to give the minimum armature current, as shown in Figure 1.

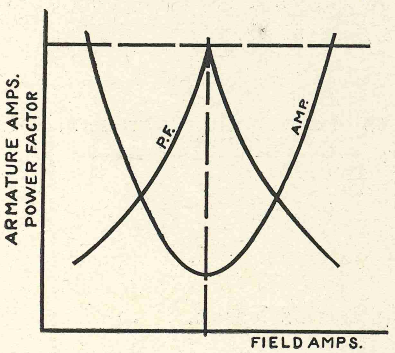
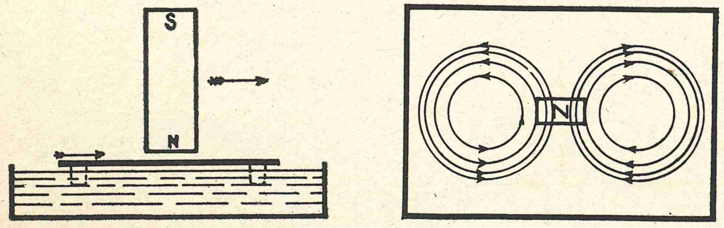


Figure 1—Curve showing Change of Armature Current and Power Factor with Field Current in a Synchronous Motor.

The installation of synchronous motors, or synchronous condensers, as they are sometimes called, will often save a Central Station company from making an addition to its generating system by improving the power factor, thus enabling the present equipment to give more power output for the same apparent watts.

Induction Motors. The type of alternating current motor most commonly used is the **Induction motor.** This is the most simple, rugged, and satisfactory of all motors.

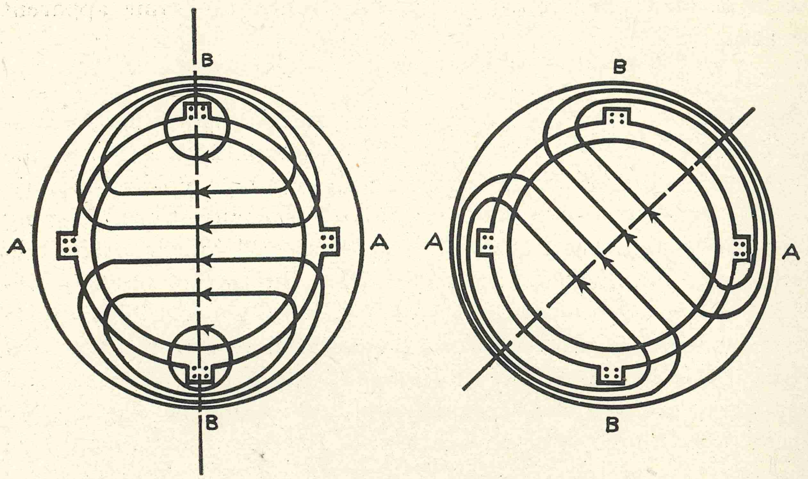
The principle of the induction motor is simply this: Moving magnetism cutting electrical conductors will induce current in the conductors in such a direction that the conductors will follow the moving magnetism. Consider Figure 2. This represents a metal sheet supported by corks floating on water. If the magnet is moved across the metal sheet, eddy currents will be set up in the metal and the metal will follow the magnet, due to the reaction between the current and the magnetism. The speed of the metal sheet will be slower than that of the magnet; otherwise the lines of force will not cut the metal and no current will be set up.



TOP VIEW EDGEWISE VIEW

Figure 2—Induction Motor Principle

With polyphase alternating currents it is a very simple matter to set up a moving magnetic field without having any moving magnets. Consider two coils with iron core arranged as shown in Figure 3 and excited by alternating current from a two-phase generator. Coil AA is connected to one phase of



1

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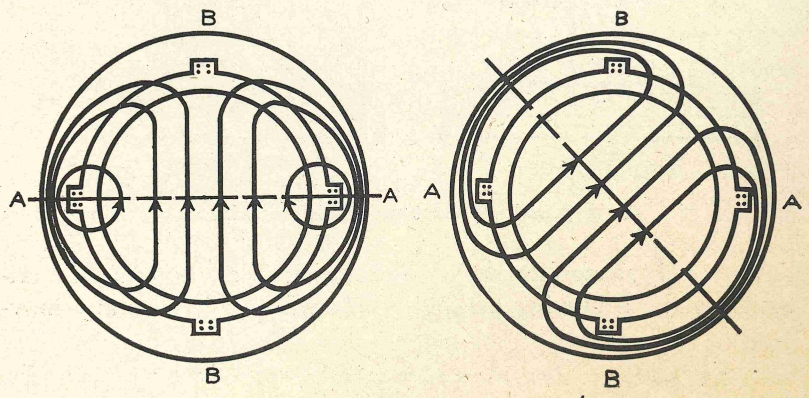
Two Fixed Coils, A A and B B, Arranged as Represented and Connected to a Two-Phase Alternating-Current Circuit Produce Changes in Magnetism as Shown



3

4

Figure 3—Rotating Magnetic Field. Simple Two-Phase Arrangement

the generator and coil BB to the other phase. At the instant marked 1 on the wave, Figure 4, the magnetism is as shown in 1 of Figure 3, one pair of poles excited by wave B has full strength and the other is at zero. The next instant (2) both poles have equal strength and the magnetism is represented in 2. In the next position (3) the first pair of poles has zero magnetism and the second set has full strength, as in 3.

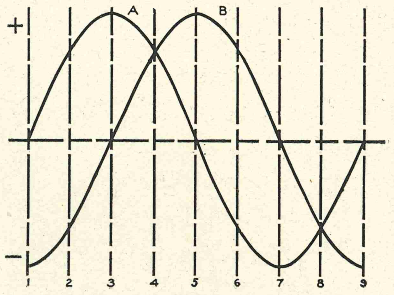


Figure 4—Two-Phase Wave

This is what is called a rotating magnetic field. Of course, there are no fixed points of change, such as marked 1, 2, 3, but the change is gradual and continual, so that the magnetism revolves around the ring at a uniform speed.

This action can be analyzed by vectors, as shown in Figure 5.

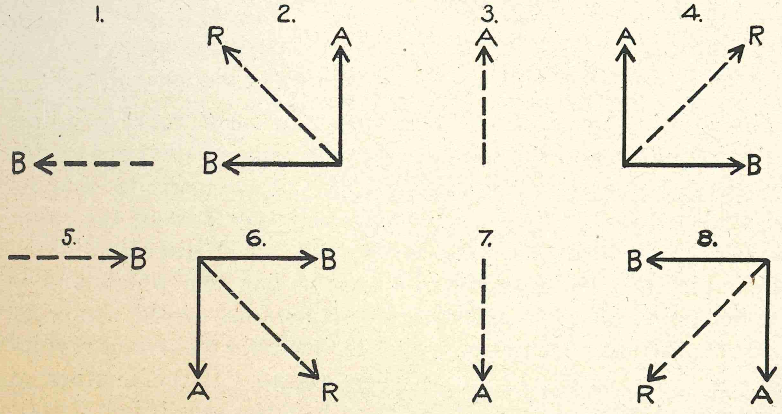


Figure 5—Vector Representation of Rotating Magnetic Field. The Numbers Correspond to the Instants Marked in Figure 4 and the Letters Refer to the Magnetism Produced in Coils A A and B B of Figure 3. R is the Resultant Magnetism.

In these figures the resultant magnetism is revolving in a clockwise direction. If an inner cylinder is mounted on a shaft and is free to revolve, it will follow the magnetic field at a slightly slower speed.

The stationary part of the motor, called the **stator,** is wound with an evenly distributed winding, as shown in Figure 6. The revolving part, called the **rotor,** in its simplest form consists of a series of copper bars, parallel to the shaft, and imbedded in the laminated iron core and short-circuited at both ends, as shown in Figure 7. This simple type is called the **squirrel-cage rotor.** The rotor may be coil-wound and is then called a **wound rotor.**

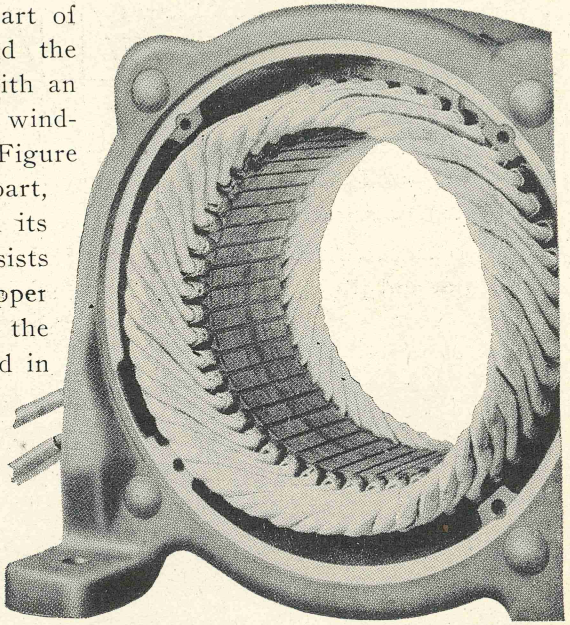


Figure 6—The Stator of an Induction Motor

The rotating magnetic field rotates at a speed corresponding to the frequency and the number of poles, and is called synchronous speed, because it is in step with the supply current; that is, run at the same speed as a synchronous motor having the same number of poles and supplied with the same frequency. Thus, the simple motor illustrated in Figure 3 has two poles, and if supplied with 60-cycle current the magnetism would rotate at 3,600 revolutions per minute. That is, it would make one revolution per cycle, or 60 revolutions per second. If the number of poles were 4, the field would rotate at half the speed, i. e., 1,800; if 8-pole, at 900; if 16-pole, at 450, etc.

As stated before, the rotor cannot run at the same speed as the rotating magnetism, because then it will cut no lines of force, and there will be no current set up in the rotor and no torque developed. This difference in speed between magnetism and rotor speed is called **slip,** i. e., the rotor slips behind. The greater the load the motor drives, the greater is the slip, the more lines of force cut, the larger the current that flows, and greater the torque developed, thus making the motor self-regulating in its demands for power.

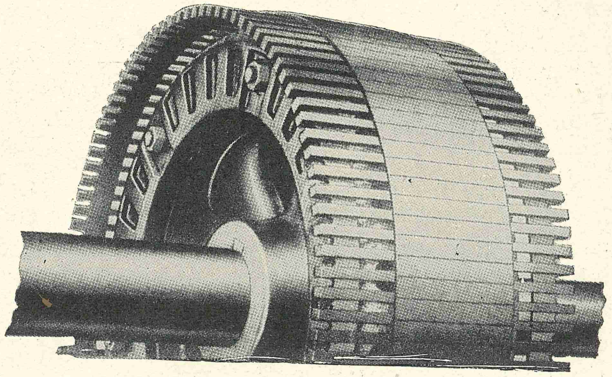


Figure 7—Squirrel-Cage Rotor

Slip is usually stated in per cent. of synchronous speed, as follows:

$$\text{Per cent. slip} = \frac{\text{Synchronous speed} - \text{actual speed}}{\text{Synchronous speed}}$$

For example, if the 2-pole motor described ran at 3,200 r. p. m., then:

$$\text{Per cent.} = \frac{3600 - 3200}{3600} = \frac{400}{3600} = 11.$$

The slip at full load, of course, will vary with the size of motor. Small motors have the higher slip and large motors the lower slip. The slip at full load is about 10 per cent. for small motors and 3 per cent. for the larger motors.

Speed Rating. Some manufacturers rate their induction motors, at synchronous speed, as 900-1,200-1,800, while others give actual full-load speed as 870-1,150-1,760, etc. The actual full-load speed is recommended by The Electric Power Club.*

---

*An association of motor manufacturers.

Speed of Induction Motor. The speed of the induction motor depends on two things, the number of poles in the stator and the frequency of the supply circuit. The expression for speed is:

$$\text{Revolutions per minute} = \frac{\text{Frequency} \times 60}{\text{Number of pairs of poles}}$$

Thus a 6-pole motor on 60 cycles,

$$\text{R. p. m.} = \frac{60 \times 60}{3} = 1200$$

That is to say; the synchronous speed is 1200 r. p. m., actual rotor speed being a few per cent. less, as explained. The following table gives the synchronous speeds of the most commonly used motors:

Number of Poles	Synchronous Speed r. p. m. 25 Cycles	60 Cycles
2	1,500	3,600
4	750	1,800
6	500	1,200
8	375	900
10	300	720

Motors must be used on approximately the frequency for which they are designed.

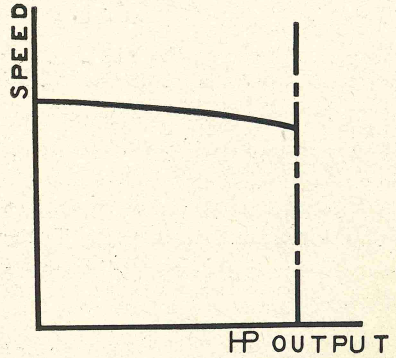


Figure 8—Speed Curve Induction Motor

Speed Characteristic of Induction Motor. Induction motors are called constant speed motors, as they have speed characteristics very similar to the d. c. shunt motor, i. e., highest speed at no load and slightly decreasing speed as the load comes on. Induction motors are, therefore, used for about the same application as direct current shunt motors. The speed-load characteristic of an induction motor is shown in Figure 8.

Torque of Induction Motors. In induction motors we are interested not only in the running torque* but also the starting torque. These may be much different, depending on the type of motor. One type will start a much larger load than it can carry when up to speed. Another may be able to carry, when up to speed, a much greater load than it can start, while another type can carry any load that it can start. It is, therefore, very necessary that the person selecting a motor, for any particular application, should understand the torque requirements of that particular load and the torque characteristics of the various motors, in order to make the best selection of motor.

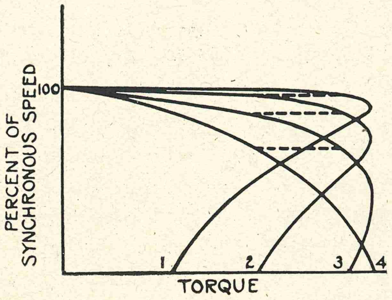


Figure 9—Speed-Torque Curves

An induction motor with a low resistance squirrel-cage rotor has a low starting torque and high running torque. Curve 1 of Figure 9 shows the relation between speed and torque for such a motor. Starting torque is low and the maximum running torque is at a point about 10 per cent. below synchronous speed. If the resistance of the rotor is made higher, by the use of longer or higher resistance conductors, then the motor will develop a higher starting torque and a lower running torque, similar to curve 2 of Figure 9. Now, if the resistance of the rotor can be made high at starting and low when up to speed, then the motor will have high starting torque and high running torque. This is accomplished by using a wound rotor and by the use of slip-rings and brushes to connect a resistance in the rotor circuit at the time of starting, gradually cutting out the resistance as the motor comes up to speed, and finally short-circuiting the slip-rings when the motor is up to full speed. The characteristic of such a motor is a combination of several characteristics, for example, starting on the highest resistance it would be on curve 4 of Figure 9 until the resistance is decreased, when it would change to curve 3 (along the dotted line) then later to curve 2 and finally to curve 1 as the slip rings are short circuited.

---

*Turning effort.

Starting Current. The starting current taken by an induction motor depends upon the type of motor and the method of starting. If a motor with low resistance, squirrel-cage rotor is thrown directly on to the full voltage without a starter, as may be done, there will be a large rush of current, from three to six times normal at low power-factor. This is very unsatisfactory, as it pulls down the voltage of the line, giving poor regulation for lighting circuits. For this reason, it is very desirable to use some form of starting device, especially on the larger motors. Some Central Station companies allow motors up to 5 h. p. to be started without the use of any device to keep down the starting current.

Starters for Squirrel Cage Motors. The most common starting device for induction motors with squirrel-cage rotors is what is called a compensator or auto-transformer.* This is a device represented in Figure 10, which transforms the voltage of the line to a low voltage for starting, and after the motor is up to speed the controller connects the motor to the full voltage. This greatly reduces the starting current.

When a compensator is used, the motor is connected through the compensator, without fuses while in the starting position, and the fuses are in the circuit only when the starter is in the running position. The reason for this is that fuses large enough to carry the starting current would not protect the motor against excessive current while running and the motor would burn out.

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*A single coil transformer with taps.

The starting compensator has taps so that it can supply several voltages. The lowest voltage that will start the motor should be used.

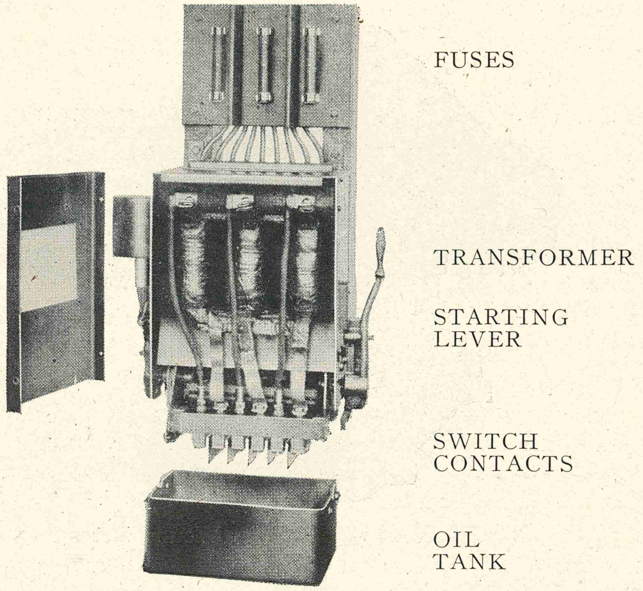

Figure 10—Starting Compensator for Three-Phase Induction Motor

Wound Rotors. For larger motors, where high starting torque is desired, the wound rotor motor is more desirable. The wound rotor is wound very much the same as the armature of a revolving armature generator, with the ends of the windings brought out to slip-rings. They are usually wound three-phase and use three slip-rings, or may be provided with an internal starter.

Where slip-rings are used, a resistance controller is connected in the circuit, so that when the circuit to the stator is closed the resistance of the rotor circuit is high and the current taken from the line is small, and the torque developed per ampere is high. As the rotor comes up to speed, the resistance is gradually cut out, until finally the rotor-winding is short-circuited.

The controller is usually of the cast-iron grid resistance type, although for very large motors liquid rheostats are often used. Figure 11 shows a motor with wound rotor.

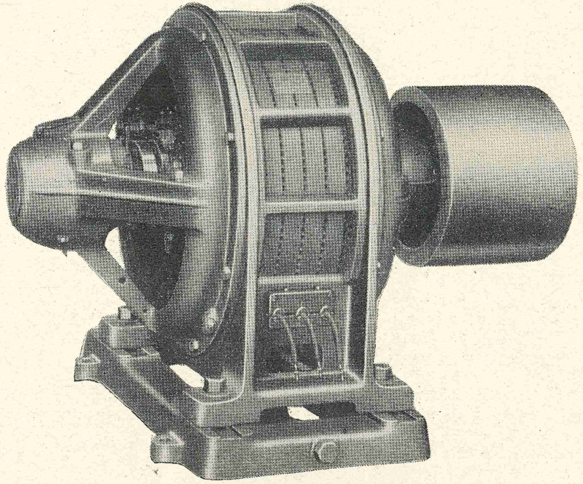

Figure 11—Motor with Wound Rotor

One of the manufacturing companies makes a line of wound rotor motors with internal starting resistance. This is controlled by a rod passing through the shaft, or by a lever. A rotor of this type is shown in Figure 12, and a motor with internal starter in Figure 13.

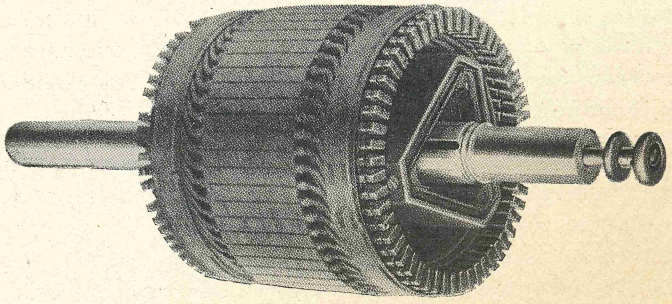

Figure 12—Wound Rotor with Internal Resistance Starter

Another manufacturing company makes this type of motor with an automatic, internal rheostat, i. e., as the motor comes up to speed the resistance in the rotor circuit is automatically reduced.

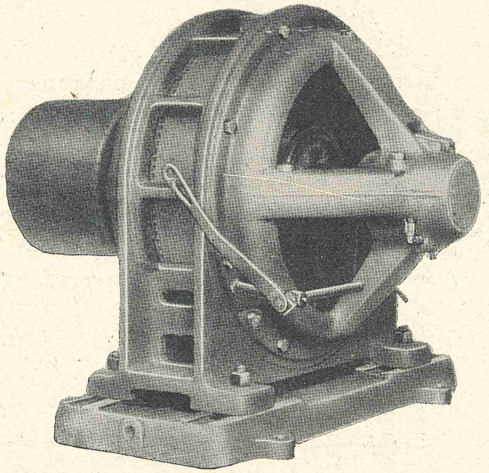

Figure 13—Motor with Internal Resistance Starter, General Electric Co.

Reversing Polyphase Motors. In general, polyphase* motors can be reversed by reversing any two phase wires. In most cases, this means reversing the connections of any two wires. In two-phase motors with each phase supplied by a separate transformer, it means reversing the connection of two wires of the same phase.

Power Factor of Induction Motors. The power factor of an induction motor is very low when running at no load or light load, but is quite high when running at or near full load. The curve Figure 14 shows the relation of power factor to load for an induction motor. This curve, while for a certain make and size of motor, is quite typical of induction motors in general.

---

*More than one phase, as two-phase or three-phase.

The curve of Figure 15 shows the relation between power factor at full load and size of motor. As might be expected, the power factor is uniformly high for all sizes of motors.

The induction motor has one peculiarity; that is, very small space between rotor and stator, so small that with a little bearing wear the rotor is likely to rub on the stator and cause trouble. This should be carefully watched. The clearance or air gap is made as small as possible in order to keep the power factor high, for with larger air gaps there is greater magnetic leakage, and whenever the magnetic leakage is large, the power factor is low.

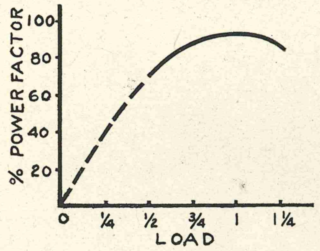

Figure 14—Power-Factor Curve for 25 h.p. Motor

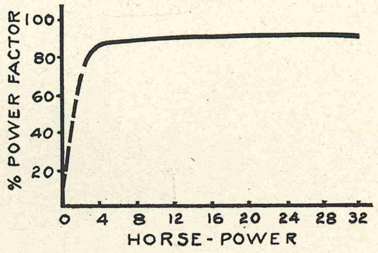

Figure 15—Relation of Power Factor to Size of Motor

Efficiency. The efficiency of induction motors is as high as for other types of motors and follows about the same relation to the load, i. e., low efficiency at light loads, high efficiency at higher loads.

Voltages. As has been stated, the induction motor is almost an ideal motor, in that it has no commutator, no slip-rings (with squirrel-cage rotor), and is about as indestructible and foolproof as it is possible to make a rotating device.

It also has the advantage that it can be easily wound for a wide range of voltages up to 11,000. The very high voltage motors are little used, but 2,300 volt motors are standard and very commonly used. This does away with the necessity of a transformer on most distributing systems.

Most induction motors are so wound that, by simply changing the connections of the coils in the stator, the same motor can be used on 110, 220, or 440 volts. It is advisable, of course, to use the higher voltage for power work, if possible, as the sizes of wire, switches, and fuses are cut down in proportion and the first cost and maintenance cost is much lower. The higher voltage of 440 is very desirable, as it makes a large saving, and is not high enough to be very dangerous, although a very uncomfortable one from which to receive a shock.

Applications. The polyphase induction motor is applicable to practically every drive where a motor can be used. The following table gives a good idea of many common applications.

Application	Starting Torque Required	Running Torque Required	Type of Polyphase Motor Suitable
Machine tools, as lathes, drill presses, milling machines, wood working machines.	Low	High	Squirrel cage low resistance rotor or wound rotor with starter.
Cranes, hoists, elevators.	High	Low	Squirrel cage high resistance rotor or wound rotor with starter.
Punches, shears.	High	High	Wound rotor with starter.

Single-Phase Motors. Single-phase motors are of many kinds, chief of which are the following:

Split-phase induction.
Repulsion.
Series.

Single-Phase Induction Motors. If, when a three-phase motor is running, one of the three fuses blows or one wire is broken, the motor will continue to run on two wires; that is as a single-phase motor. Of course, it will not be able to carry full load without overheating the motor. If the motor is allowed to stop and then the switch is closed with only two wires connected, the motor will not start. That is to say,

a single-phase induction motor is not self-starting. If, however, the rotor is turned rapidly by hand, in either direction, the motor will rapidly accelerate and attain full speed. That is, it will run in either direction, depending on which way it is started.

It is, of course, not feasible to start any except the very small motors by hand; therefore this method of starting is little used and some auxiliary starting method must be used.

The reason for the single-phase motor not being able to start without a special device is that a single-phase current does not set up rotating field, as does the polyphase current. The field set up by a single-phase current is pulsating, i. e., simply back and forth.

Split-Phase Motors. By providing the motor with two sets of windings, similar to those of a two-phase motor and supplying one phase with current directly from the line and the other phase with current slightly out of phase with the line current, but from the same single-phase source, a more or less moving field can be developed. Only a slight difference in phase will produce enough of a moving field to develop sufficient torque for starting the motor without load. A three-phase motor can be made to start on single-phase by using the phase-splitting arrangement shown in Figure 16. After the motor is up to speed the phase-splitting device can be disconnected. A large number of the manufacturers make motors of this type. With some a double throw switch is used, one side for starting and the other side for running. Sufficient phase displacement for starting can be obtained by having the motor wound for two-phase with different impedance in the two windings. Many motors are constructed this way and use a centrifugal switch within the motor, which opens the auxiliary phase when the motor attains a certain speed.

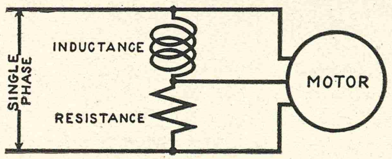

Figure 16—Phase Splitting Arrangement

Some motors are provided with an automatic friction clutch pulley, so that the motor starts without load and takes on the load automatically after reaching a certain speed. All of these are split-phase motors.

The split-phase motor is very satisfactory for small motors up to few horse power if polyphase current is not available. They are never so satisfactory as polyphase motors because of the auxiliary device required.

Repulsion Type. If the regular rotor of a single-phase induction motor is replaced by a direct-current armature and the brushes of this armature short-circuited, currents are induced in the armature by the changing magnetism set up in the stator. There is a strong torque developed, due to the repulsion between the currents induced in the armature and the field set up by the stator. This torque produces rotation. This is the principle of the **Repulsion Motor.** In other words, the repulsion motor has the regular single-phase stator and an armature with commutator, wound like a direct current armature. The brushes connected to the commutator are not connected to the line, but are short-circuited.

The repulsion motor is used quite generally, but not so much as the split-phase induction type.

One excellent type of motor starts as a repulsion motor, and when it is nearly up to speed, a centrifugal device throws the brushes away from the commutator and short-circuits all of the bars of the commutator, thus converting the motor into an induction motor. That is, the motor starts as a repulsion motor and runs as an induction motor. This motor is shown in Figure 17.

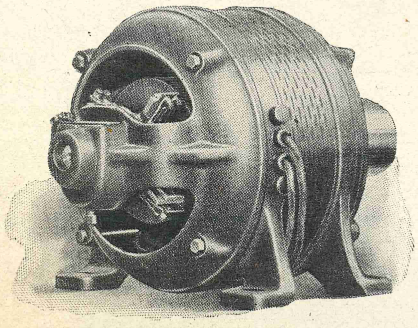

Figure 17—Repulsion Induction Motor.—Wagner Electric Co.

Series A. C. Motors. The series motor used on alternating current is very similar to the series direct-current motor. It differs in that the field structure is made up entirely of laminated iron,* and that there are additional windings on the stator to reduce the self-induction of the armature. It has practically the same operating characteristics as a series d-c. motor, having high speed at light load and low speed at heavy load.

This type of motor is used quite extensively for single-phase railway work. High voltage alternating current as 11,000 volts is used on the trolley between cities, and the same motor is run on 500 volts direct current within the city limits. Of course, control equipment used on direct current is different from that used on alternating current.

Figure 18 is a picture of an interurban car equipped with series a. c. motors running on 11,000 volt trolley.

This same type of motor is also called the **universal motor,** as it can be run on direct or alternating current. It is quite extensively used on household appliances, such as vacuum cleaners and sewing machines.

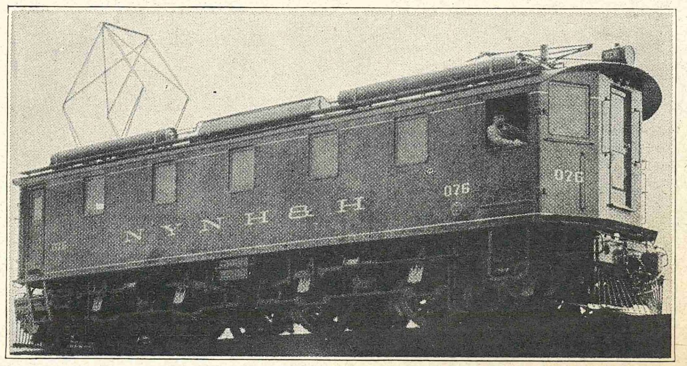

Figure 18—110-Ton Baldwin-Westinghouse 11,000-Volt, Single-Phase 25-Cycle Locomotive, Equipped with Four Westinghouse 340-h. p. Single-Phase Motor Units and Unit Switch Control

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*Punchings of thin sheet iron.

Reversing Rotation of Single-Phase Motors. The direction of rotation of a single-phase, split-phase, induction motor can be reversed by reversing connections of either the main or the auxiliary winding. Repulsion motors can be reversed by shifting the brushes as marked.

Series a-c. motors can be reversed by reversing the connections of either field or armature.

Advantages of Single-phase. For the smaller motors, single-phase motors have a decided advantage over three-phase from the Central Station company's point of view, because they can be supplied from single-phase lighting circuits and therefore do not require running the third wire and do not require at least two transformers, as do three-phase motors. The larger amperage required by a single-phase motor and the unbalancing of the three-phase load will more than offset the above mentioned advantages on larger motors.

Relative Costs of Single and Polyphase Motors. From the purchaser's point of view, the single-phase motor is at a disadvantage because of higher first cost and usually higher upkeep cost because of the fact that the single-phase motor is more complicated in construction than the two or three phase motors. The first cost of single-phase motors will generally be from 25 to 50 per cent greater than the cost of a polyphase motor of the same capacity .

Speed Control of A. C. Motors. There are no simple satisfactory methods of speed control for polyphase induction motors. The methods that can be used are the following:

Adjusting stator voltage.
Adjusting rotor resistance.
Changing frequency.
Changing number of poles.

Adjusting Stator Voltage. This can be done by a transformer or by resistance. This gives a range of speed from zero to normal and has many disadvantages; namely, poor speed regulation and low efficiency, and is little used except as a method for starting a. c. motors.

Adjusting Rotor Resistance. This is used with wound rotors and use is made of a variable resistance in the rotor circuit. The arrangement is the same as that used for starting wound-rotor motors, except that the resistance is so designed as to carry full-load current continuously. This method is not suitable for use on motors driving machine-tools, as the speed changes greatly with change in the load. It is, however, well adapted for use on cranes, hoists, elevators, and applications where the torque required of the motor is constant, or nearly so. This method is commonly used.

Changing Frequency. As has been stated, the speed of an induction motor is proportional to the frequency supplied to it. This, then, gives a very good method of speed control if it is feasible to vary the frequency of the supply circuit. This requires a frequency changer or separate generator for each motor. This can be used only for large motors on very important work. It is seldom used.

Changing Number of Poles. If an induction motor is wound with a large number of poles, then it is possible to bring out the winding connections so as to change the number of poles by proper switching arrangements. Thus a 60 cycle motor wound for a maximum of 8 poles could be run at the following speeds: 8 pole, 900 r. p. m.; 4 pole, 1,800 r. p. m.; 2 pole, 3,600 r. p. m. This is a very efficient and satisfactory method except that for wide range of speed it greatly complicates motor construction. This method is also little used and when used is most often for two speeds only.

Conclusion on A. C. Motor Speed Control. From the foregoing statements it will be concluded that while there are several possible methods of speed control of polyphase induction motors, the only method used to any extent is the resistance in rotor circuit method, and this method is not applicable to loads such as machine tools, for which speed control is very desirable. This leaves the adjustable speed propositions almost entirely to direct current motors.

Single-Phase Adjustable Speed Motors. There are a number of adjustable speed single-phase motors on the market and for small power these are very satisfactory. The methods in general use are:

Shifting the brushes on series a-c. motors.
Varying the voltage applied to motors.

Shifting the Brushes. This method is quite commonly used on motors up to 7½ horse power and is especially useful for driving printing-presses and similar work where a range of speed from synchronous speed to one-half synchronous speed is desired. For the smaller motors the speed range by this method may be as high as 4 to 1.

Varying the Voltage. Using a series a-c. motor and changing the voltage applied by means of a transformer, gives a range of speed as high as 4 to 1, with satisfactory operation.

Comparison of Direct and Alternating-Current Motors. Practically the only advantage that the direct-current motor has over the alternating is in the matter of speed control. Where adjustable speed through a wide range is required the direct-current motor is the more satisfactory.

The alternating-current motor, especially the polyphase induction motor, has a decided advantage over direct-current motors on account of its great simplicity and rugged construction. The fact that it has no commutator, slip-rings, or brushes, makes the squirrel cage type of motor especially desirable for many applications.

DEMONSTRATION FOR LESSON VI.

1. Take a small induction motor apart to show the construction.

2. Same for starting-compensator.

3. Show how a three-phase motor will run on single-phase, but will not start alone as a single-phase motor. Start by hand.

4. Show several types of single-phase motors, if possible.

REFERENCE BOOKS.

Electricity Experimentally and Practically Applied, by Sidney W. Ashe, D. Van Nostrand Co., New York.

Applied Electricity for Practical Men, by Arthur J. Rowland, McGraw-Hill Book Co., New York.

Elements of Electricity and Magnetism, by Franklin and McNutt, McMillan Co., New York.

Elements of Electricity, by Timbie, McMillan Co., New York.

Elements of Electricity and Magnetism, by D. C. and Wm. B. Jackson, McMillan Co., New York.

Continuous and Alternating Current Machinery, by J. H. Morecroft, John Wiley & Sons, New York.

Alternating Currents, by George T. Hanchett, John Wiley & Sons, New York.

The Induction Motor, by A. B. Behrend, McGraw-Hill Pub. Co., New York.

The Induction Motor, by Benj. F. Bailey, McGraw-Hill Pub. Co., New York.

Alternating Current Electric Motors, by A. H. McAllister, McGraw-Hill Pub. Co., New York.

QUESTIONS.

Note: These questions are to be answered after the lesson has been studied carefully, and without further reference to the lesson.

1. What is a synchronous motor?

2. How can a synchronous motor be used to adjust power-factor?

3. Explain, briefly, the principle of the polyphase induction motor.

4. What determines the speed of an induction motor?

5. A 4 pole, 10 horse power induction motor is connected to a 30 cycle circuit. What is the no load speed? What is the approximate full load speed?

6. How are induction motors started?

7. Explain, briefly, the action of a split-phase motor.

8. Compare, briefly, alternating current motors and direct current motors as to speed control.

INDEX.

	Page
Applications	17
Comparison of D. C. and A. C. Motors	23
Efficiency	16
Induction Motors	5
Power-factor of Induction Motors	15
Regulation of Power-factor	4
Repulsion Type Motors	19
Reversing, Polyphase Motors	15
Reversing Single-phase Motors	21
Series A. C. Motors	20
Single-phase Adjustable Speed Motors	23
Single-phase Motors	17
Speed Characteristics of Induction Motor	10
Speed Control of A. C. Motors	21
Speed of Induction Motor	10
Speed Rating	9
Split-phase Motors	18
Starters	12
Starting Current	12
Synchronous Motors	3
Torque of Induction Motors	11
Types of Alternating Current Motors	3
Voltages	16
Wound Rotors	13

NOTICE.

Special sheets for answers to test questions have been sent to you. These answers should be sent to the Chairman within 30 days. They will be corrected, graded and returned to you direct or through your class leader.

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LESSON V : Alternating-Current Generators and Principles

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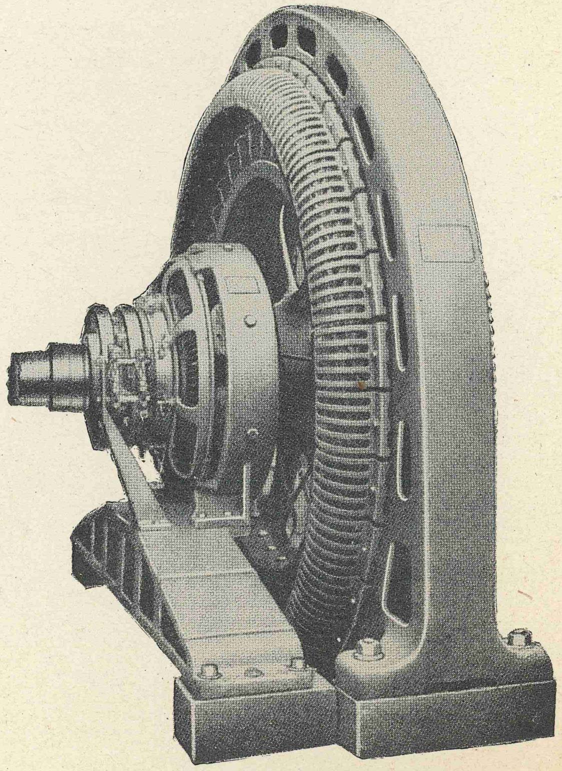
INTRODUCTION

Alternating current is now used so generally, that every one in the electrical industry should be familiar with the fundamental principles and the more common pieces of apparatus.



Engine Driven Revolving-Field Type Alternator, with Exciter on the Same Shaft

NATIONAL ELECTRIC LIGHT ASSOCIATION COURSE IN PRACTICAL ELECTRICITY.

LESSON V—ALTERNATING-CURRENT GENERATORS AND PRINCIPLES.

Electric Generators. The reader should bear in mind the statement made in Lesson III that the **electric generator is merely a piece of apparatus used to convert mechanical energy into electrical energy.** Electric generators are of two general classes—direct current and alternating current. These names refer to the character of the current taken from the generator. It will be remembered that alternating current is generated in a conductor that cuts lines of force first under a north pole and then under a south pole and that, in the direct-current generators, this alternating current is changed to direct current, in the outside circuit, by means of the commutator. Figure 1 represents a conductor cutting lines of force between a north and a south pole. For one-half of the revolution the current is in one direction and for the other half of the revolution the current flows in the opposite direction. Moreover, as was found in Lesson III this current changes in value as represented graphically by the curve of Figure 1. That is to say, the current

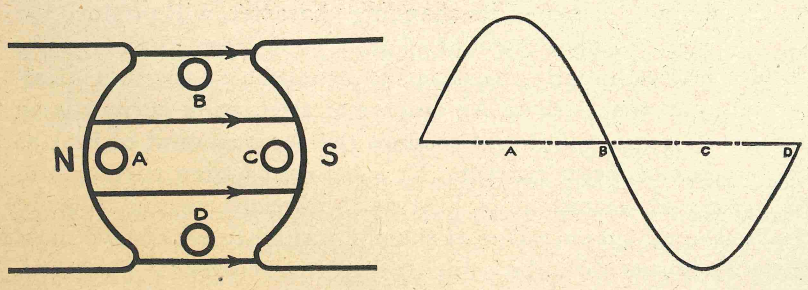


Figure 1—Conductor Cutting Lines of Force and the Voltage Wave

or voltage induced in the conductor is maximum at A, decreases to zero at B, reverses and increases to a maximum in the opposite direction at C, and decreases to zero at D, and returns to the starting point again at A. If this wave of voltage or current follows the shape shown in the figure it is called a sine wave of voltage or current. The waves of commercial machines only approximate this theoretical wave, and are very likely to have shapes such as are illustrated in Figure 2. The shape of the wave depends upon the design and construction of the generator and also upon the character of the load on the machine.

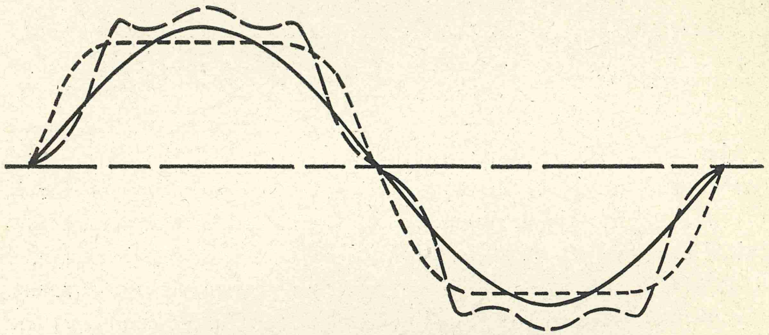


Figure 2—Wave Shapes

All calculations are based on the Sine wave.

Heating Effect of A. C. Current. The question often arises in the student's mind as to whether or not an alternating current, because of its changing character, will produce the same amount of heat as a direct current. The answer is **Yes,** exactly, because the definition of the unit of alternating current is this: **An ampere of alternating current is an amount of current that will produce the same amount of heat as one ampere of direct current.** Now if the changing current produces the same amount of heat as the steady current, then of course the maximum value of the alternating-current wave must be much higher than the value of the direct current. The maximum value on the sine wave is 1.41 times the value indicated on a meter.

Effective Values. These values are represented in Figure 3. The highest point of the wave is called the **maximum value.** The value measured by the voltmeter or the ammeter is called the **mean effective** or sometimes, the **Square Root of the mean square value.** For a Sine wave, the theoretical wave shown, the **mean effective value** is found to be **0.707 of the maximum.** That is to say if the maximum value was 100 volts then the voltmeter would give a steady reading of 70.7 volts or with an alternating current having a maximum value of 100 amperes, the heating effect would be the same as of 70.7 ampere of direct current, therefore our alternating-current ammeter must read 70.7 amperes also. If the effective value is 0.707 of the maximum, then of course, **the maximum is 1.41 times the effective value,** i. e., if the effective value is 100 volts then the maximum on the Sine wave would be 141. volts. This means that with an alternating current we must insulate for 41 per cent higher voltage than for direct current of the same rating, also that a shock from an alternating current is more dangerous than from direct current of the same rated voltage, because of this high maximum value. Keep in mind that the relations just given between maximum and effective values apply exactly only to Sine waves (theoretical waves) and that in practice the relations are usually approximately the same.

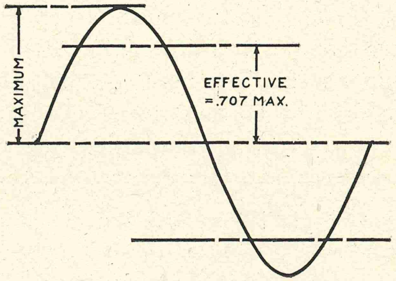


Figure 3—Sine Wave Values

Cycle—Frequency—Alternation. When the conductor has passed through **one complete set of changes,** as represented in Figure 1, the voltage or current **is** said to have passed through **one cycle.** That is, **one cycle of voltage or current is generated when a conductor passes from a point under one pole to the corresponding point under the next similar pole.** The cycle represented in Figure 1 is generated in a conductor as it makes one complete revolution. If, however, there were four poles instead of two, it would make only half a revolution for each complete cycle.

The number of cycles generated per second is the Frequency. Thus, a 60 cycle generator is one in which the voltage and current pass through 60 complete sets of changes, or 60 cycles per second. The voltage and current change or alternate twice per cycle. There are, then, twice as many alternations as cycles. It is customary to speak of **cycles per second** and **alternations per minute.** That is, if a generator generates 60 cycles per second it generates 7,200 alternations per minute, and it is spoken of as generating 60 cycles or 7,200 alternations. Most manufacturing companies rate the generators in cycles; a few, however, rate in alternations.

The frequency of any alternating-current generator can be found from the following expression:

$$\text{Frequency} = \frac{\text{Number of poles}}{2} \times \frac{\text{r. p. m.*}}{60}$$

Thus, if a generator having 2 poles, revolves at 3,600 r. p. m., then:

$$\text{Frequency} = \frac{2}{2} \times \frac{3600}{60} = 60 \text{ cycles.}$$

Choice of Frequency. The first alternators in general use supplied current at higher frequencies than are now used; that is, at frequencies of 125 to 133 cycles. The frequencies now used in this country are from 25 to 60.

It is a well known fact that at very low frequencies, such as 10 cycles per second, there is a very noticeable fluttering of the light from electric lamps. This of course is very tiring to the eyes. At frequencies as high as 25 this noticeable flutter disappears, but it is possible that it still has an effect on the eyes, though the fluctuations are too rapid to be seen. At 60 cycles it is believed that the changes in light are too rapid to have any effect on the eyes.

The low frequencies are most desirable for power purposes, as low speed motors are more easily and cheaply built. Low frequencies also are better for transmission systems. Where the load on a station is principally all power, as in large manufacturing districts, frequencies of 15 to 30 are commonly used. Where the load is combination light and power, a frequency of 60 is most common. In fact, 60 cycle current is used by probably 75 per cent of the Central Station companies supplying both light and power. A number of the largest companies use two frequencies, such as 25 and 60. The lower frequency is supplied to rotary converters to convert to direct current and to frequency changers, and the higher frequency is used for the alternating current districts for both light and power.

---

* r. p. m. means Revolutions Per Minute of a revolving part.

Simple Alternating-Current Generators. If we consider a single coil, as represented in Figure 4, connected to a pair of slip-rings and revolving in a magnetic field, the current generated will be alternating and follow approximately the wave shown in Figure 4. This is known as a **single-phase current.**

If there are two such coils placed on the armature 90 degrees apart, each coil connected to a pair of slip rings, then we have two separate phases, or what is called **two-phase** current, and the waves are as represented in Figure 5 and separated by 90 degrees. That is to say, when one coil is in the horizontal position and cutting lines of force at the greatest rate, the other coil is in the vertical position and is cutting no lines of force and generates no voltage at that instant.

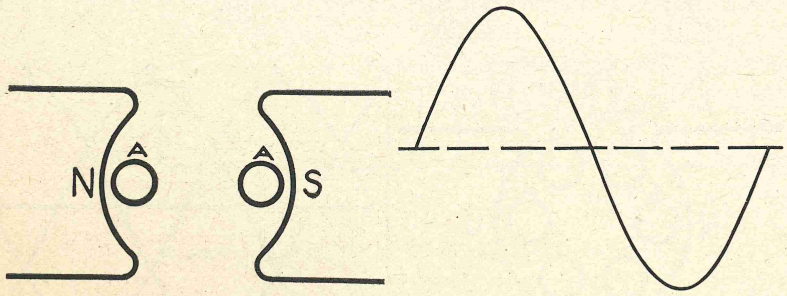


Figure 4—Simple Single-Phase Generator and Wave

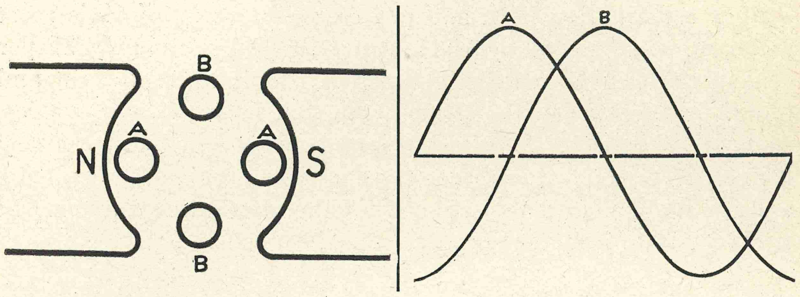


Figure 5—Simple Two-Phase Generator and Waves

If three coils are placed on the armature and spaced as shown in Figure 6, then we have three separate sources of current, with a 120 degree relation between the voltages or currents, or what is called **three-phase current,** the three waves being as represented in Figure 6. These have been represented for a machine having a two-pole field. If the machine had a four-pole field, there would be twice as many coils, so as to have the same relation between the currents in the different phases, or if it were a six-pole generator there would be three times as many poles and three times as many sets of coils, so that the electrical relation between them would be the same as for a two-pole generator.

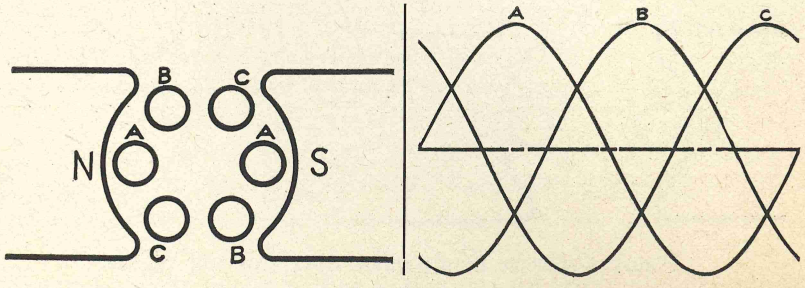
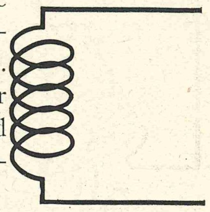
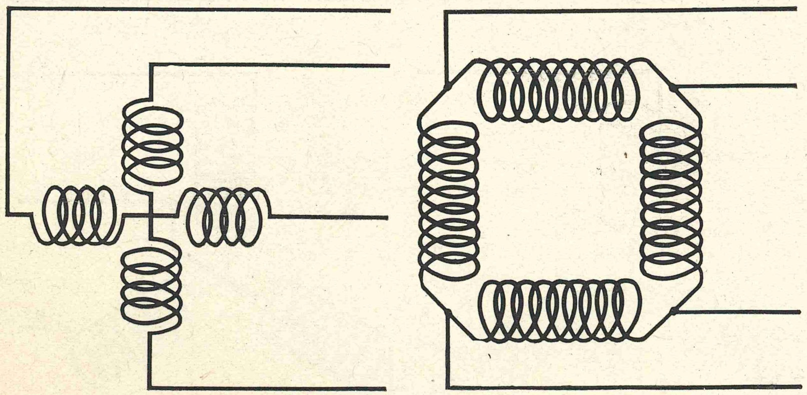


Fig. 6—Simple Three-Phase Generator and Waves

Connections. The single-phase generator has two wires from its armature, while the two-phase generator may have three or four. Usually four wires are brought from the generator and these may be connected to form three mains, outside of the generator, if the phase windings are not connected inside of the generator. The three-phase generator may have three or four wires. The connections for single, two and three-phase generators are represented diagrammatically in Figures 7 and 8.



Single-Phase

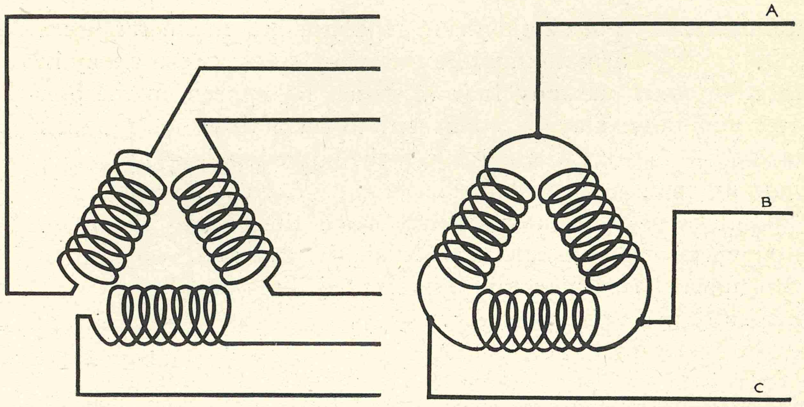


Two-Phase Two-Phase

Figure 7—Single and Two-Phase Connections

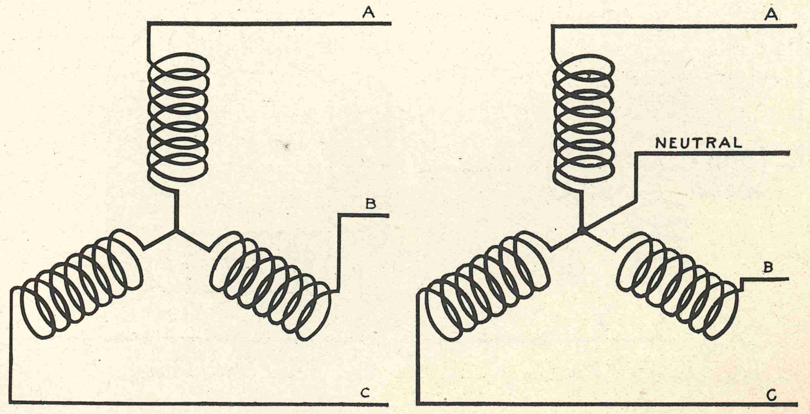
Here each coil represents the complete phase winding. These may be combined as shown.

Three-Phase Connections. Consider a simple three-phase generator, having three coils 120 degees apart, as represented in Figure 8. How can these be connected? First of all, we could bring out two wires from each coil, or a total of six. Or adjacent wires could be combined, making a total of three wires.



Three-Phase Six Wire

Three-Phase Delta



Three-Phase Star or
Y—Three Wire

Three-Phase Star or
Y—Four wire

Figure 8—Three-Phase Connections

The second connection is called **Delta,** because the three coils form the sides of an equilateral triangle or delta. The corresponding wires of the three coils may be connected together to form a neutral, with the three remaining wires used as the mains. This is called the **Star** or **Y** connection. Sometimes the neutral or a fourth wire is brought out, giving a four-wire three-phase system. With a given voltage and current per coil, the voltage and current in the line will, of course, depend upon which connection is used.

Three-Phase Voltage and Current Relations. If the three coils or phases of a generator are **Delta** connected the voltage between the lines is the same as that of the coils, while the current in each line will be 1.73 times that of the current in each coil as the current from two adjacent coils combine.

If the three phases are star or Y connected, then the voltage between the lines is greater than that of each coil, i. e., the line voltage equals the phase voltage multiplied by 1.73. The current in each line will be the same as the current in each coil.

Most three-phase generators are star or Y connected.

Mechanical Arrangement of Parts. Alternating-current generators are classified according to the mechanical arrangement of parts, as follows:

Revolving-Armature type.
Revolving-Field type.
Inductor type.

Revolving-Armature Type. This is the generator that is most like the direct-current generator. It has the same type of field poles and the same type of armature, with the exception that there are slip rings in place of the

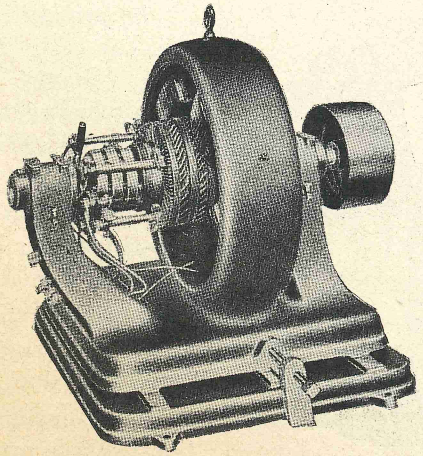


Figure 9—Revolving-Armature Type Alternator—Belt Driven

commutator. This type is used only for very small machines. Figure 9 shows a generator of the revolving-armature type. This also has a commutator to supply direct current for the field winding.

Revolving-Field Type. The revolving-field type differs from the revolving-armature type in that the armature or part in which the current is generated is stationary and the magnetic poles revolve as shown in Figure 10.

The armature conductors are placed in slots in the stationary part and would be practically the same as though the armature were to revolve.

The field poles are mounted on the shaft, with the field coils connected to the slip-rings through which direct current is supplied.

The revolving-field type is the type most generally used, as it has the following advantages over the revolving armature:

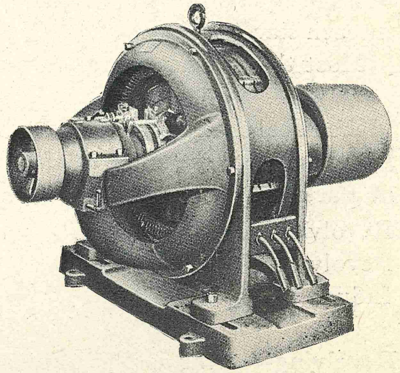


Figure 10—Small Revolving-Field Type Alternator—Belt Driven

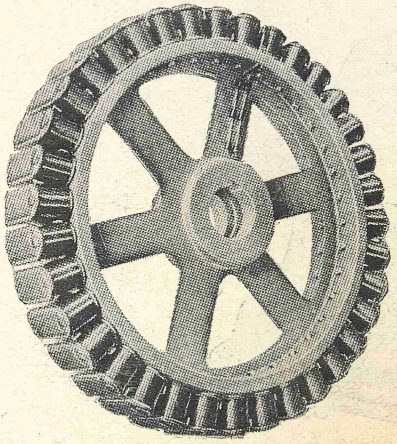


Figure 11—Revolving Field for Large Engine-Driven Generator

The armature being stationary, can easily be insulated for high voltages. This type is often constructed to generate 10,000 to 15,000 volts.

There are no exposed high voltage parts, as there are no slip-rings and brushes of the revolving-armature type.

The field can easily be constructed to stand the mechanical strain due to rotation.

Cast iron slip-rings with carbon brushes can be used in the field circuit, and these are practically an ideal combination for wear, but could not be used on the revolving-armature type.

NOTE:—The generators shown are General Electric Co. types.

Figure 11 shows the revolving field of a large engine-driven alternator. This field has 36 poles, and the generator will generate 60 cycle current if run at 200 revolutions per minute.

Inductor Type. In this type both the armature conductors and field windings were stationary. Only a mass of iron similar to a flywheel with projecting poles revolved. This is now obsolete, as the mechanical construction was expensive and the regulation of voltage rather unsatisfactory.

Factors Determining Voltage. As might be expected, the same factors that determine the voltage of a direct-current generator determine the voltage of the alternating-current generator. These factors are **magnetic flux, speed,** and **number of conductors in series.** In the alternating-current generator there is another factor, called **phase relation,** that enters into consideration. In direct-current circuits, the total voltage across a group of coils is the sum of the separate voltages, but this is seldom the case in alternating-current circuits, as will be seen later.

Methods of Excitation. The source of supply of direct current for field excitation of alternators is a very important thing. Most of the larger generators are provided with a direct-current generator mounted on the same shaft. In addition to this a power plant has motor-driven exciters, engine or turbine-driven exciters, and in the very large plants a storage battery.

In case of failure of other sources of direct current, the battery, which is always connected to the excitation bus, will supply current to the fields without interruption.

ALTERNATING-CURRENT PRINCIPLES

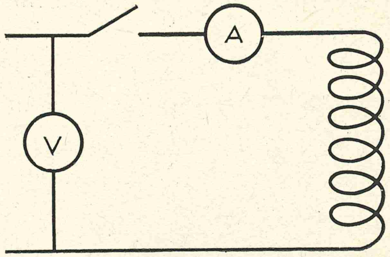


Figure 12—Inductive Circuit

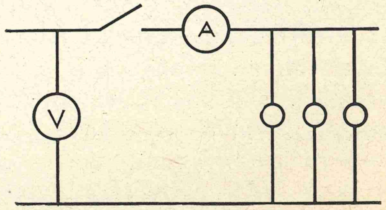


Figure 13—Non-Inductive Circuit

Induction. The flow of electricity is not instantaneous, as is often believed. A very appreciable time is required for current to flow, especially under certain conditions. Consider, for example, the field coil of a d. c. shunt dynamo. This, as we know, is made up of a large number of turns of small wire, wound on an iron core. Connect this up as shown in Figure 12 with an ammeter and voltmeter and switch in the circuit. If the reading of the ammeter is noted for some time after the switch is closed, it will be seen that the ammeter needle moves very slowly and does not come to its full reading for possibly several seconds, depending upon the kind of a coil in the circuit. If the switch is opened quickly, it will be noted that a long arc is drawn out. If the switch on a lamp circuit, such as shown in Figure 13, taking the same current, is closed and opened, the ammeter needle moves up more rapidly and practically no arc is drawn on opening the switch, although both circuits carry the same current at the same voltage. What is the reason? Simply this: In the field coil we are setting up a strong magnetic field and these lines of force cut the turns of the coil and set up or induce a voltage that opposes the change in the current. When the switch is closed, this induced voltage tends to keep down the current, that is, opposes it, and when the circuit is opened the induced voltage tries to keep the current flowing. The greater the number of turns in the coil, the more noticeable is this effect. **This effect is called Self-induction.** The changing magnetic field induces voltage in the coil itself. This voltage induced in a shunt field winding is usually very high and dangerous. It is what is sometimes called the "kick of the field." It reaches values of several thousands of volts and is therefore dangerous to the insulation of the field as well as to life. The amount of this voltage depends upon two factors, the amount of magnetism and the rate at which it changes. It is, therefore, well to open field switches slowly or provide them with special switches that short circuit the field windings as soon as the current is cut off, thus allowing the field current to gradually die down. Large dynamos are equipped with such switches. Note that this voltage can be induced in the winding only while the current is changing. After the current reaches a steady value there is no such self-induced voltage. Now, with an alternating current, the current is changing all of the time, and very rapidly. Therefore the effect of self-induction becomes very important in alternating-current circuits.

If the shunt field coil previously considered was connected to a 115 volt d-c. circuit and the current flowing was 10 amperes, and the same coil were then connected to 115 volts, alternating-current circuit, it would be found that the current flowing would be only a very small fraction of an ampere, possible 1-100th of an ampere. The reason for the difference on the alternating current is that the electro-motive-force set up by self-induction on account of the rapid reversal of the alternating current keeps the current down to a very low value. From this it can be seen that in alternating current work we must consider not only the ohms resistance of a circuit but also another factor called the **Inductance.**

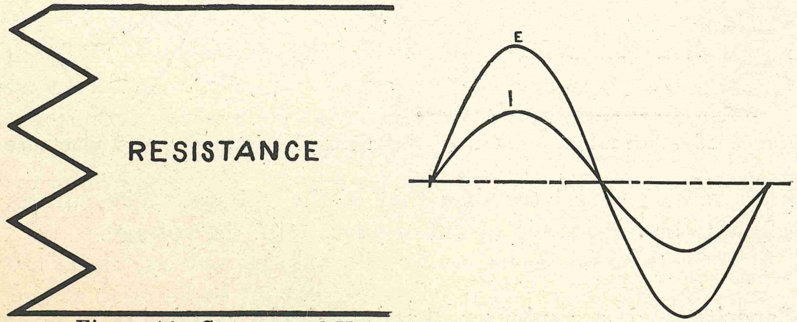


Figure 14—Current and Voltage Relations—Resistance Only

The inductance of an alternating-current circuit depends upon the character of the circuit whether made up of lamps or coils of wire on iron cores and also upon the frequency of the circuit to which it is connected.

The effect of inductance is to cause the current in the circuit to lag behind the voltage of the circuit. That is to say, the voltage reaches its maximum value before the current does. This lag may be great or little, depending upon the inductance of the circuit. If the circuit is composed of lamps, the voltage and current changes are practically together as represented by the voltage and current waves of Figure 14. They are said to be in phase. If the inductance of the circuit is large, the current will lag behind, as represented in Figure 15; that is, its maximum value comes later than that of the voltage. The current is said to be out of step or out of phase with the voltage.

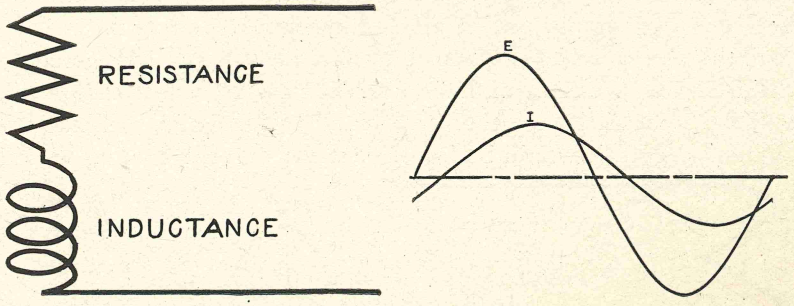


Figure 15—Current and Voltage Relations—Resistance and Inductance

Capacity. If a condenser, that is, a device consisting of large metal plates, insulated from each other and connected as shown in Figure 16, is placed in a direct current circuit no current will flow, the lamp will not light. If, however, it is connected to an alternating current circuit, current will flow and the lamp is lighted. The plates of the condenser, when connected to the direct current circuit, become charged; that is, current flows onto the plates for an instant and then stops. If the condenser is taken out of the direct current circuit and its terminals connected by a wire there will be a spark, or discharge of the condenser. When the condenser is connected in an alternating current circuit there is a continual charging and discharging, and while no current flows through the insulation between the plates of the condenser, there is a flow of current back and forth through the lamp.

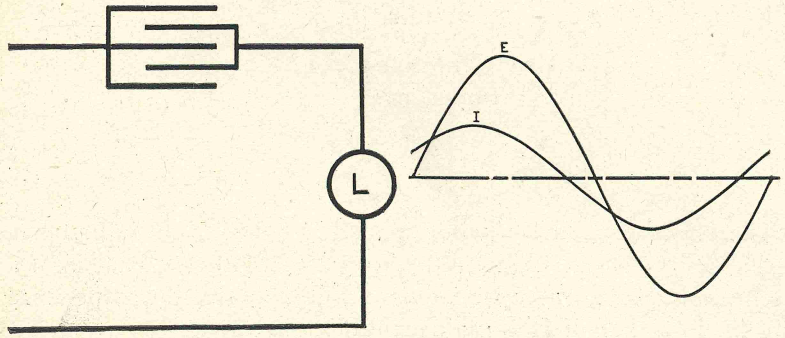


Figure 16—Current and Voltage Relations—Capacity

It is found that the effect of a condenser is just the opposite of the effect of an inductance. Instead of the current lagging behind the voltage it precedes or leads the voltage. When the condenser has the least voltage applied there is the greatest flow of current; that is, the maximum of current occurs before the maximum of voltage. This is represented by the waves of Figure 16.

We see, then, that the quantity of current in a direct current circuit is determined by the resistance alone, while in an alternating current circuit the quantity of current is determined by resistance, inductance and capacitance. **The terms inductance and capacitance are combined in a term called reactance, while the terms resistance, inductance and capacitance are combined in one term impedence.**

Ohm's law for alternating-current circuits will differ from that for direct-current circuits.

For direct-current circuits.

$$\text{Current} = \frac{\text{Electro-motive-force}}{\text{Resistance}}$$

$$I = \frac{E}{R}$$

For alternating-current circuits.

$$\text{Current} = \frac{\text{Electro-motive-force}}{\text{Impedence}}$$

$$I = \frac{E}{Z}$$

The effect of capacity being opposite of that of an inductance it can easily be seen that one may offset the other. That is, if a circuit contains both capacitance and inductance, the impedence will be less than if it contained either one alone.

Power in A. C. Circuits. In all direct-current circuits, the power in watts is always equal to the product of the voltage multiplied by the current. This is sometimes true in an alternating-current circuit, i. e., in a circuit containing resistance only. If the circuit contains inductance or capacitance then the product of E and I does not give the watts in the circuit. The watts in the circuit with a given voltage and current may be anything from zero to the product of E and I. This can be seen by a careful study of the following figures. Figure 17 represents the voltage and current in a circuit containing resistance only. It will be noticed that the current and voltage waves have their zero and maximum values at the same time in the same direction; that is, the current is in phase with the voltage. The watts at any instant would be the product of the instantaneous values of voltage and current. The dotted curve represents the products of the instantaneous values of E and I. The products of e and i are all positive and the power as shown by a watt meter would be the average of the power loops. Assuming that the effective value of the voltage is 100 and of current 50, then the average watts in this case is equal to 5,000.

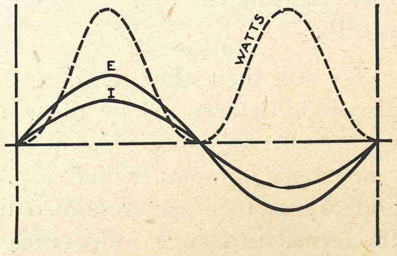


Figure 17—Current, Voltage and Power—Resistance Only

The left-hand set of curves, Figure 18, represents the same values of voltage and current supplied to a circuit containing some inductance. The effect of this inductance is to cause the current to lag, or be behind the voltage. Let us assume this lag to be 30 degrees as represented, then the power wave (product of instantaneous values of E and I) is part positive and part negative. The reading of a wattmeter would be the average of these positive and negative values and would be much lower than in the case previously considered. The voltage is still 100 and the current is still 50, but the average power as shown by a watt meter would be 4,330. Now consider the right-hand set of curves of Figure 18, which represents a circuit practically all inductance and almost no resistance; that is to say, a coil of large wire on an iron core. The current in this case would lag practically 90 degrees as represented. The power wave would have as large a power loop negative as positive and the average power would be zero watts, although the voltage is still 100 and the current is still 50 amperes. The same reasoning would apply if we substitute capacity for inductance.

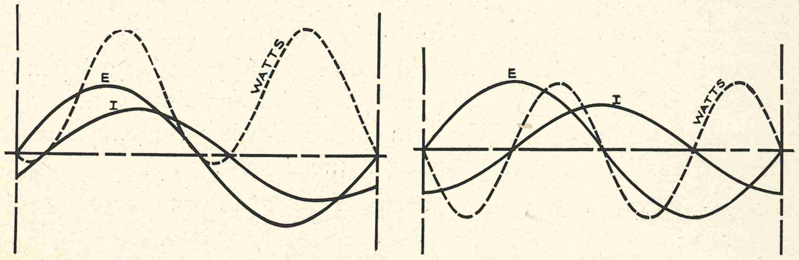


Figure 18—Current, Voltage and Power—Inductance

Power Factor. In an alternating-current circuit, the amount of current flowing depends upon three factors; namely, **Voltage, Resistance,** and **Reactance.**

If the circuit contains coils of wire, the current is choked back and reduced. This effect is called **Induction.** If the circuit contains a condenser,* or capacity, the current is ahead and increased. This effect is called capacity.

In a direct-current circuit the amount of power in the circuit can be found by measuring amperes and volts and multiplying the one by the other, that is **Watts** $= E \times I$. On account of the effect of inductance and capacity, this relation does not hold for an alternating current circuit.

Power in an alternating-current circuit is usually determined by using a watt meter, and the power is given by the expression:

$$\text{Watts} = \text{Volts} \times \text{Amperes} \times \text{Power Factor}$$

Power Factor has a numerical value of unity or less, depending upon the nature of the circuit. This means simply that the product of volts and amperes, in an alternating current circuit, is never less than the true watts in the circuit.

$$\text{True Watts} = \text{Apparent Watts} \times \text{Power Factor}$$

or

$$\text{Power Factor} = \frac{\text{True Watts}}{\text{Apparent Watts}}$$

$$\text{Power Factor} = \frac{\text{True Watts (by Watt Meter)}}{\text{Volts} \times \text{Amperes}}$$

Relation of Currents and Voltages in Series Circuits. Currents and voltage relations in alternating current circuits are much different than in direct current circuits. Consider a simple series circuit as represented in Figure 19. The current in all parts of the circuit is, of course, the same. If each unit had resistance only, the sum of the separate voltages would equal the line voltage, but since the units represented are coils of wire and have resistance and inductance, then the sum of the separate voltages will be higher than the line voltage. These voltages instead of adding up arithmetically, as in direct current circuits, add up geometrically. That is to say, each voltage can be represented by a line, the length of which is proportional to the voltage and the direction of which shows the phase angle between the current and the voltage. For example, if each unit of the circuit is represented, the voltage

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*A condenser consists of alternate metal plates insulated from each other.

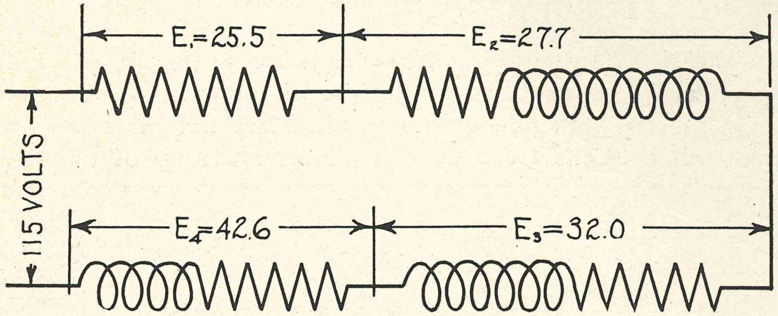

Figure 19—Series A. C. Circuit

of the parts would be as shown in Figure 20. Unit No. 1 has resistance only, therefore the current and voltage are in phase as represented in No. 1 of Figure 20. The second unit is largely inductance, therefore its current lags nearly 90 degrees behind the voltage across the unit, as shown in No. 2. Unit No. 3 is a balance of resistance and inductance and is represented geometrically in No. 3. Unit No. 4 is largely resistance and the current lag is small, as represented in No. 4. Now all of these voltages add together geometrically or Vectorially* as is commonly stated, and placing these lines properly we get the combined diagram of Figure 21. This shows each separate voltage in value and direction and the resultant voltage is the line voltage. That is to say, the Vector sum is 115. volts, while the arithmetical sum is 127.8 volts. It will be noticed that the resultant voltage is out of phase with the current, i. e., the current lags behind the voltage about 30 degrees.

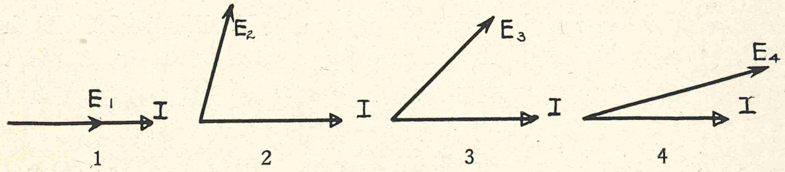

Figure 20—Voltage Vectors, Series Circuits

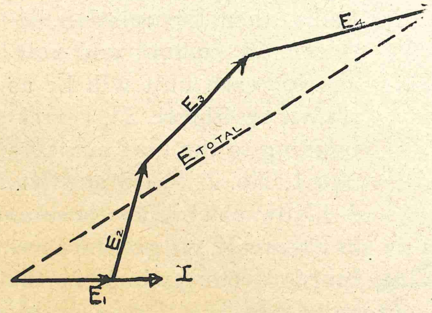

Figure 21—Voltage Relations—Series Circuit

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*A line representing the value and direction of a quantity is called a vector.

Parallel A. C. Circuits. In parallel alternating-current circuits, all of the units or parts of the circuit receive the same voltage, but the currents are not in phase with each other. Consider a parallel circuit made up of the same units as in the series circuits and represented in Figure 22. Each of these now receives the line voltage, therefore the current through each is independent of the other. If the impedence of each of the separate units is as follows, No. 1 = 25.5, No. 2 = 27.7, No. 3 = 32 and No. 4 = 42.6 ohms, then the relation between the current and voltage for each unit will be as shown in Figure 23, corresponding to the unit numbers No. 1, No. 2, No. 3 and No. 4. Now combining these as in Figure 24, we get the combined Vector, which is the value and direction of the total current in the main line. The Vector sum of these currents is 13.5 amperes, while the arithmetical sum is 15. amperes.

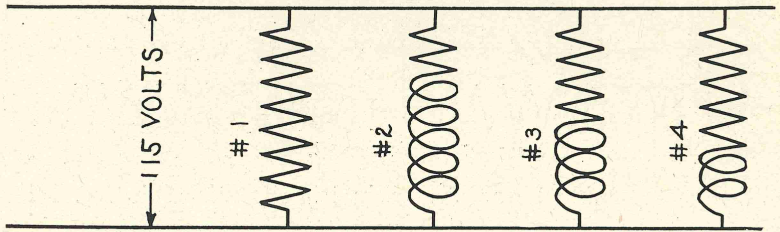

Figure 22—Parallel A. C. Circuits

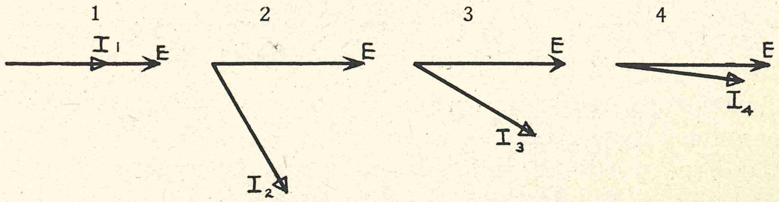

Figure 23—Current Vectors—Parallel Circuits

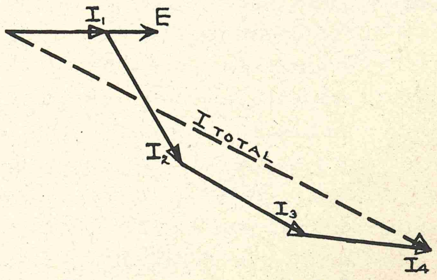

Figure 24—Current Relation—Parallel Circuit

This is so much different from the simple relation between current and voltage in direct current circuits that it may be confusing to the student. The first thing the student should learn is that the facts as applied to direct current circuits do not apply to alternating current circuits and he should then study these pages carefully. If he wishes to pursue the study farther than the possible scope of this lesson, he should study some of the references given at the end of this lesson.

Measurement of Power in A. C. Circuits* Due to the fact that the product of volts and amperes will seldom equal the watts in an alternating current circuit, it is necessary to use a special instrument known as the Wattmeter, for making power measurements. This instrument has a current coil and a voltage coil and the reading is at all times proportional to the average power in the circuit.

By the use of ammeter, voltmeter and wattmeter the power factor of a circuit can be determined from the equation:

$$\text{Power Factor} = \frac{\text{Wattmeter reading}}{\text{Volts} \times \text{Amperes}}$$

Wattless Current. Because volts times amperes does not give the true watts, it is considered that a portion of the current does not represent any power; that is, part of the current is a power or watt current, while the remainder is a wattless current. Take, for example, the case mentioned on page 19, where the current of 50 amperes lagged thirty degrees behind the pressure of 100 volts. The apparent watts are 5,000 but the true watts, as measured by a watt meter, are 4,330.

The power-factor is equal to:

$$\frac{\text{True watts}}{\text{Apparent watts}} = \frac{4330}{5000} = 0.866$$

or 86.6 per cent. From Ohm's law, the power component of the current would be 43.3 amperes, since 43.3 × 100 = 4,330, the true watts. Furthermore, it is evident that this power component must be in phase with the voltage.

The vector diagram would appear as in Figure 25, in which I_1 represents the power component of current, I_2 would then represent that component of current I, which is at right angles

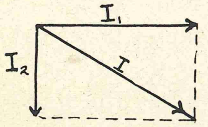

Figure 25

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*This subject will be treated fully in Lesson IX—Measurement of Power.

to I_1. Hence, it must lag behind the voltage E by 90 degrees also and therefore can represent no power, as was shown on page 19 and in Figure 18. This is called the wattless component of current. Since Figure 25 is a rectangle, the value of I_2 may be found from I_1 and I.*

$$I_2^2 = I^2 - I_1^2 = (50 \times 50) - (43.3 \times 43.3)$$
$$= 2500 - 1875 = 625$$
$$I_2 = \sqrt{625} = 25 \text{ amperes}$$

the wattless component of current in this case.

Effect of Wattless Current. As has been stated before, the heating of any wire is proportional to the square of the current. Now the current heats and also causes a voltage loss whether it is wattless or not, therefore, if a given load has a very low power-factor, that is, carries a large wattless current, then there will be a corresponding loss in heating the line wires and a corresponding drop in voltage on those lines and all of the other load, such as lamps, will be given poor voltage regulation.

Another evil is that the generators and transformers are fully loaded when they reach the heating limit, no matter whether the current is a power or a wattless current. That is to say a 1,000 kw. generator having a load of 1,000 kilovolt amperes is fully loaded, although the watt meter may show that it is actually delivering only 750 kilowatts, which would mean that the engine was not fully loaded and the company was not getting full benefit of its investment. Therefore Central Station companies try to keep the power factor as high as possible. This is done by properly balancing inductance and capacity and refusing to take on loads of very low power factors, such as electric welders, and certain kinds of electric furnaces, and certain motor loads. The incandescent lighting load is a unity power-factor load, and as will be found in our next lesson, certain types of motors have high power factors, while some may be used to offset the low power factor of others.

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*It is known in geometry that in a rectangle the square of the diagonal is equal to the sum of the squares of the two dimensions of the rectangle.

Rating of Alternators. From what has been said regarding power factor it is seen that the useful output of a generator depends upon the character of the load. This means that a given generator may be capable of carrrying a load of 10,000 kilowatt, but if the power factor is 80 per cent its full load is 8,000 kw.; if the power factor is 75 per cent, the generator is carrying full load at 7,500 kw. This necessitated a statement regarding the power factor of the load on which a generator was to be used, when a generator was ordered. For example: A generator to be ordered would be required to deliver 10,000 kw. at 80 per cent power factor, and it would have entirely a different rating at some other power factor. To avoid such confusion, a new rating has been standardized and is known as the kv. a., or kilovolt-ampere rating. This is the product of volts and amperes divided by 1,000. Power factor does not enter into the question. When a generator is carrying full load current and full load voltage it is fully loaded regardless of the actual **kilowatts** or true output.

Parallel Operation of Alternators. The same necessity for operating generators in parallel is found with alternating current as with direct, but the principle and method of operation are quite different.

Generators to operate well in parallel should have:

Same voltage.

Same frequency.

Same or similar wave shape.

Waves in synchronism (same time relation) when the switch between them is closed.

Voltage and frequency are matters of design and regulation. Wave shape is a matter of design alone. If two machines have waves of much different shape, there will be a large interchange of current between them which will overheat the generators and cause much trouble.

Providing the two machines have proper voltage, frequency and wave shape, then to parallel them is only a question of synchronizing. This means that the two generators should have their waves in exactly the same condition at the same instant the machines are connected together. If this is not the case there may be an enormous rush of current, practically a short circuit between the two machines that will do much damage. This proper condition is determined by means of synchronizing lamps or a synchroscope.

Consider the case represented by Figure 26. Generator No. 1 has been running on the load and it is desired to connect No. 2 in parallel with No. 1. If lamps of the proper voltage are connected across the switch of No. 2 as shown, then by aid of these lamps we can determine the proper instant at which to close the switch.

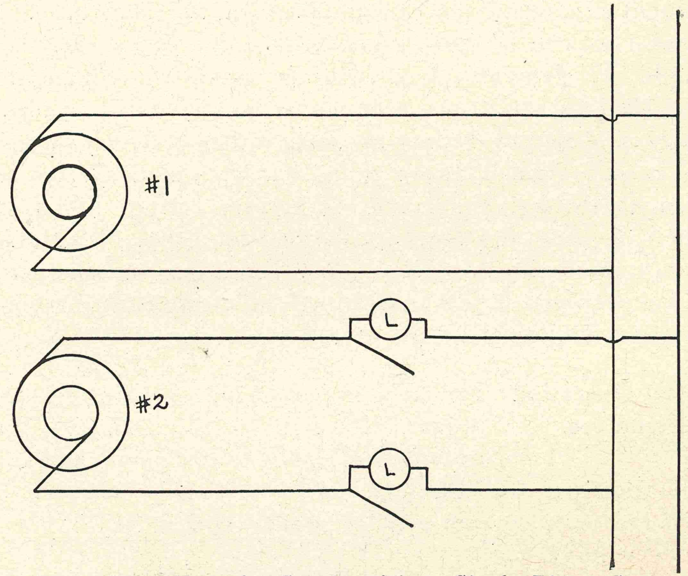

Figure 26—Connections for Synchronizing—Single Phase Generators

As generator No. 2 is brought up to full voltage and speed, the lamps will be seen to flicker rapidly. As the frequency of No. 2 comes closer and closer to that of No. 1 the flicker becomes slower and slower until the lamp finally remains bright for considerable time and then dark for considerable time. When the lamps are dark is the proper instant to close the switch, for at this instant the wave of No. 1 and No. 2 are in exact step with each other, that is they oppose each other across the lamp and the lamp is dark. After the switch has been closed it will be noticed that No. 2 does not take its share of the load. This can be regulated by changing the speed of the engine or other prime mover connected to the generator. Delivering more power to the generator which it is desired to have carry the greater load, causes its wave to move slightly ahead of that of the other generator with a resulting change in the load. The governors of turbines and engines are usually under control of the switch-board operator so that he can change their speeds while synchronizing or shift the load from one generator to the other at will.

The method of synchronizing just described is for two single phase generators. If two three-phase generators are to be synchronized there should be one set of lamps for each phase, as it is necessary that all of the phases be in synchronism. With proper connection for synchronizing all three sets of lamps will be bright or dark together. If the lamps alternate in being bright and dark it indicates that one pair of wires must be reversed before the machines can be synchronized.

Synchroscope. The lamp method of synchronizing is not very generally used at it is not very accurate because there can be quite a large phase difference between machines while the lamps are still dark. If two machines are connected together while the phase difference is large there is a very violent motor action developed that pulls the machines into step. This may be so violent as to wreck the machines or cause other serious trouble.

The device most commonly used is the synchroscope. This is an indicating instrument and consists of a motor driven by the two generators to be synchronized. The instrument is so designed that it indicates the phase difference between the machines at any instant and whether the incoming ma-

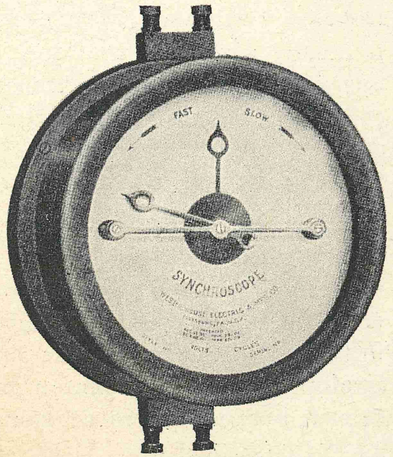

Figure 27—Westinghouse Synchroscope

chine is running fast or slow. The switch of the incoming machine is closed when the hand is on zero. One type of synchroscope is shown in Figure 27.

There is an automatic synchronizer on the market, i. e., a device which automatically closes the main switch at the proper instant. This device is very complicated and is not generally used.

Choice of System. Direct current is suitable for general light and power service only where the distance of distribution is comparatively short, that is, where the territory to be covered is small. Direct-current systems will be found in general use in isolated plants for large buildings, for factory plants, for small towns, and in the large cities for the down-town or congested portion of the city.

Where electrical energy must be distributed over a large area or transmitted for long distances, alternating current is always used.* The reason for this is that the losses in transmission and distribution are proportional to the square of the current and as the voltages at which direct current can be used are low and because it is difficult to raise or lower these voltages, the currents are large and the losses prohibitive for long distances. With the alternating-current system the voltage can be easily changed from low to high or vice versa, and the energy can therefore be transmitted at high voltage, low current and then distributed over shorter distances at lower voltages and higher currents. Figure 28 shows the flexibility of the alternating-current system in this respect.

When electricity first came into use for light and power, direct current was the only form used. This accounts for many of our older systems being direct current. The alternating current was first used as single-phase, later as two-phase and finally as three-phase. The single-phase systems are now practically obsolete, the reason being that it is not suitable for power because of more complicated motors being required.

---

*American Practice.

Two-phase has also almost entirely gone out of use until now almost every a-c. system is three-phase. One of the principal reasons for this is that the three-phase system requires only seventy-five per cent of the copper required for direct-current, single-phase or two-phase distribution or transmission systems, using the same voltage between lines and it meets all other requirements as well or better than any other kind of service.

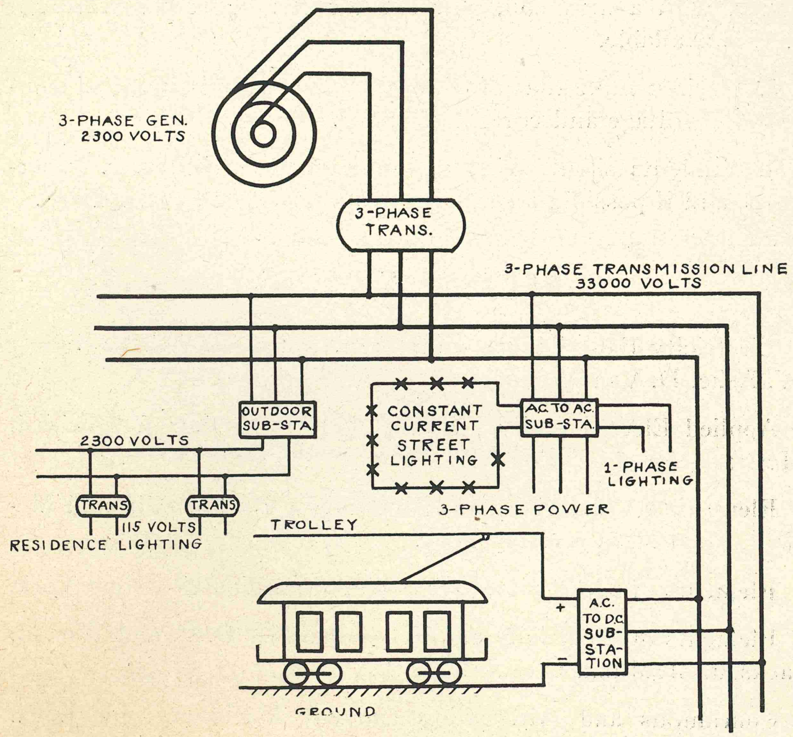

Figure 28—Alternating Current System

DEMONSTRATION FOR LESSON V.

1. Inductive effect of a coil can be shown with any shunt-motor field circuit as explained on page 14.

2. By using an indicating watt-meter, ammeter and voltmeter, with a field coil, power-factor can be demonstrated, if a. c. is available.

3. A circuit like that of Figure 19 can easily be used to demonstrate voltage and current relations.

4. Students should visit a power plant having a. c. generators, and if possible should see two alternators synchronized.

REFERENCE BOOKS.

Electricity Experimentally and Practically Applied, by Sidney W. Ashe, D. Van Nostrand Co., New York.

Applied Electricity for Practical Men, by Arthur J. Rowland, McGraw-Hill Book Co., New York.

Elements of Electricity and Magnetism, By Franklin and McNutt, McMillan Co., New York.

Elements of Electricity, by Timbie, McMillian Co., New York.

Elements of Electricity and Magnetism, by D. C. and Wm. B. Jackson, McMillan Co., New York.

Continuous and Alternating Current Machinery, by J. H. Morecroft, John Wiley & Sons, New York.

Alternating Currents, by George T. Hanchett, John Wiley & Sons, New York.

Essentials of Alternating Currents, by Timbie and Higbie, John Wiley and Sons, New York.

QUESTIONS.

Note: These questions are to be answered after the lesson has been studied carefully, and without further reference to the lesson.

1. How does an alternating current generator differ from a direct current generator?

2. Why is the revolving-field type most generally used?

3. Explain fully, how it is possible to have the true watts less than the apparent watts, in an a. c. circuit.

4. (a) What is meant by power factor?
   (b) What determines power factor?

5. Explain why a high power factor load is desirable.

6. (a) What is meant by frequency?
   (b) What frequencies are most common?

7. Why is three-phase current most generally used?

8. Discuss the parallel operation of alternating current generators.

INDEX.

Page

Alternating Current Generators, Simple 7
Capacity 16
Choice of System 28
Connections 9
Current and Voltage Relations 11, 20
Cycle, Frequency, Alternation 5
Effective Value 5
Electric Generators 3
Excitation, Methods of 13
Factors Determining Voltage 13
Frequency, Choice of 6
Heating Effect of A. C. Current 4
Induction 14
Inductor Type 13
Parallel Operation of Alternators 25
Power in A. C. Circuits 18, 23
Power-factor 19
Rating of Alternators 25
Revolving Armature Type 11
Revolving Field Type 12
Synchroscope 27
Voltage and Current Relations 11, 20
Wattless Current 23

NOTICE.

Special sheets for answers to test questions have been sent to you. These answers should be sent to the Chairman within 30 days. They will be corrected, graded and returned to you direct or through your class leader.

Certificates will be granted to those obtaining an average grade of 70 per cent or over.

Change of address must be reported to the Chairman by separate letter.

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LESSON IV : : DIRECT-CURRENT MOTORS

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INTRODUCTION.

The subject of electric motors is one of the most interesting and also one of the most valuable to be considered in this course. The student will find that a thorough knowledge of motors will be of great value to him, and he should, therefore, exert every effort to master the fundamental principles set forth in this lesson.

NATIONAL ELECTRIC LIGHT ASSOCIATION
COURSE IN PRACTICAL ELECTRICITY

LESSON IV—DIRECT-CURRENT MOTORS*

Definition of Electric Motor. **An Electric Motor is a device for converting electrical energy into mechanical energy.** It is exactly the converse of the electric generator. The direct current motor is identically the same in construction as the direct current generator. The only difference is in the manner of use. The term Dynamo is used to designate a machine that can be used as either a generator or a motor. In case the dynamo is used as a generator, mechanical energy is supplied to it and it delivers electrical energy, whereas, with the motor, electrical energy is supplied to the dynamo and it delivers mechanical energy.

In both cases, there must be some loss of energy in the transformation. In large dynamos the loss is about 10 per cent, while in small dynamos it may be as high as 50 per cent.

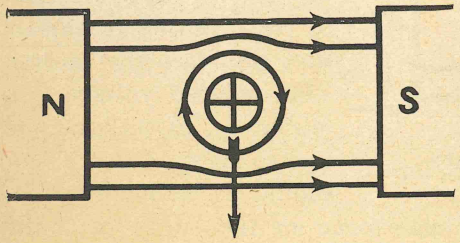


Figure 1—Motor Action

Motor Action. If a conductor carrying current is placed in a magnetic field, as illustrated in Figure 1 it will be found that a force exists that tends to move the conductor out of the magnetic field. This force is the reaction between the magnetic field surrounding the conductor and the magnetic field between the poles. The direction of this force depends upon the relative direction of the two magnetic fields.

---

*Commonly called direct-current motors, but more properly called continuous-current motors.

The reason for this is that: **Lines of force parallel and in the same direction repel** and **lines of force parallel and opposite in direction, attract.** This same law, of course, applies here. Consider Figure 1.

We have two magnetic fields, one between the poles and one around the conductor, due to the current that it carries. There is a reaction between these two magnetic fields that produces motion, as indicated. As will be seen from the law stated above, the direction of motion must depend upon the relative direction of current in the conductor and the magnetic field, between [illegible] poles. **The direction of motion can be changed either by reversing the current in the conductor, or by reversing the magnetic field. Reversing both leaves them relatively the same and the direction of motion is not changed.**

Counter-Electro-Motive-Force. If the conductor shown in Figure 1 moves as a result of the current flowing in it, it must cut lines of force. We have learned that when a conductor cuts lines of force a voltage is generated in it. Figure 2 shows the same conductor in the same magnetic field as shown in Figure 1. Applying the screw rule, we see that the voltage induced in the conductor is opposite to the direction of current that produces the motion. This induced voltage in a motor is called counter-electro-motive-force and should be well understood because it is of greatest importance in the study of motor principles.

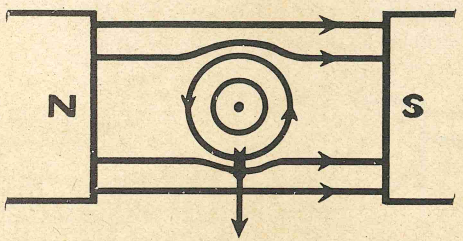


Figure 2—Counter-Electro-Motive-Force

The resistance of the armature of a motor is very small, always less than an ohm, and therefore the current that would flow in the armature would be very large if it were not for this counter electro-motive-force. Only a small part of the voltage applied to the motor is used in overcoming the resistance of the armature and the larger part is used to overcome the counter electro-motive-force, as shown below.

$$\left.\begin{array}{l}\text{Voltage applied to}\\ \text{armature when run-}\\ \text{ning at normal speed.}\end{array}\right\} = \left\{\begin{array}{l}\text{Voltage lost}\\ \text{in armature re-}\\ \text{sistance.}\end{array}\right\} + \left\{\begin{array}{l}\text{Counter}\\ \text{Electro-Motive-}\\ \text{Force.}\end{array}\right\}$$

$$E_x = R_a\,I_a + \text{C. E. M. F.}$$

Where $E_x =$ Line voltage

Where $R_a\,I_a =$ Voltage drop in armature

At no load on a 115 volt motor

$$E_x = 115$$

$$R_a\,I_a = 1 \text{ volt (approximately)}$$

$$\text{C. E. M. F.} = 114 \text{ (approximately)}$$

$$115 = 1 + 114.$$

That is, one volt or less is used to send the small current through the armature resistance and the remainder 114. (approximately) will be used to overcome the counter E. M. F.

The exact values of the $R_a\,I_a$ drop and counter E. M. F. depend, of course, on the size and design of the motor.

As load is placed on the motor, it starts to slow down, and the counter E. M. F. (which, of course, depends on the speed) will therefore be less and allow more current to pass through the armature, thus delivering the desired amount of power. The relations between the various voltages will then be about as follows, at full load:

$$E_x = R_a\,I_a + \text{C. E. M. F.}$$

$$115 = 3. + 112.$$

This shows how the motor is self-regulating, how it takes just the amount of current required to drive the load placed upon it.

Types of Motors. The types of direct current motors are the same as direct current generators, namely: **Series, Shunt,** and **Compound.** That is, the methods of connecting the field windings are the same as used for generators.

Each type of motor has quite a distinct speed characteristic and each is therefore especially suited for some particular application.

Series Motor. The series motor, as the series generator, has its field winding connected in series with its armature, as shown in Figure 3. This means that the strength of its field will depend upon the load and vary with it, with the result that the speed will be high on light loads and low on heavy loads, as represented in the curve of Figure 3. In other words, the series motor is a varying speed motor and is suited only for work in which such a characteristic is desirable. Such a motor is especially suited for **street-railway work, cranes,** and **hoists**; for in these applications we are starting a heavy load from a standstill. We desire a large amount of power at low speed, as the load decreases, the speed increases, which is what is wanted. As a street car goes up hill, the load increases and the car slows down; as the car reaches the level the speed again increases.

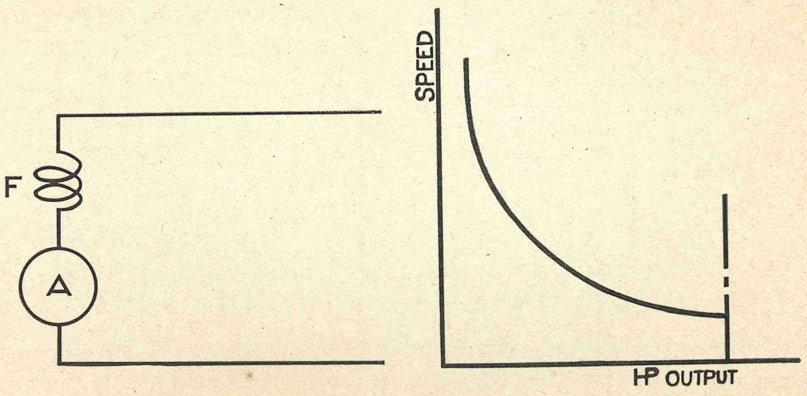


Figure 3—Connections for Series Motor with Speed Characteristic

Series motors should never be belted to their load, as, in case the belt should run off or break, there would be no load on the motor and the speed might be great enough to wreck the motor.

The Shunt Motor. The shunt motor is connected as shown in Figure 4, and, as will be seen, the field receives full voltage all of the time, and its field current is therefore constant. The speed-load characteristic of a shunt motor is therefore much different from that of the series motor, and is shown in the curve of Figure 4. The shunt motor is called a **constant speed motor** because its speed is practically constant at all loads. It will be noticed, however, that the speed falls a few per cent. as the load comes up to full value.

The **shunt motor** is therefore especially suited to power applications requiring constant speed, such as machine-shop and wood-working shop tools, printing-presses, etc. It is very simple and very generally used, especially in the smaller sizes. Unlike the series motor, the shunt motor will not run away if the load is entirely removed.

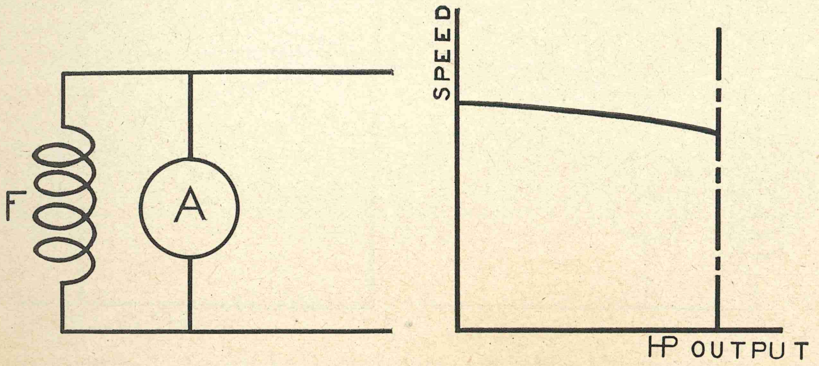
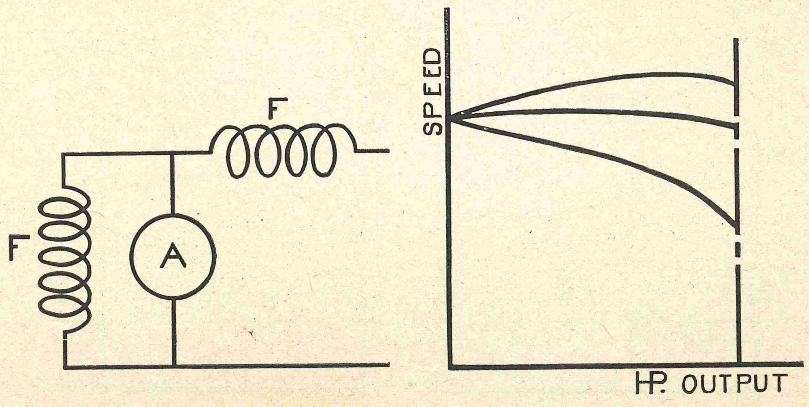


Figure 4—Connections for Shunt Motor and Speed Characteristic.

Compound Motors. Compound motors are connected like compound generators, as shown in Figure 5. There are two possible connections of the series field, one, such that the magnetism furnished by the series field will help the shunt field, strengthening the field as the load comes on and called **Accumulative Compound** (because the magnetism accumulates as the load comes on), and the other or reverse connection, in which the magnetism supplied by the series field opposes that of the shunt field and weakens the field as the load increases. This is called **Differential Compound.** The two manners of connection give quite different characteristics, as shown in the curves of Figure 5.

As compared with the same motor used as a shunt motor, the accumulatively compound gives lower speeds and the differentially compound higher speeds. This can be easily understood when it is remembered that stronger field magnetism means lower speed, and weaker field means higher speed.

Accumulative Compound motors are very generally used, especially in large motors and for work in which a large starting effort is required. With a strong field, such as is produced by the series winding a powerful torque* is developed on starting.



Upper Curves—Differential.
Lower Curve—Accumulative.

Figure 5—Connections for Compound Motor with speed characteristics

Compound motors are especially valuable on machines such as power punches and shears, which have heavy fly-wheels to start. For passenger elevators, they are also valuable because they develop good starting torque, and, after the car is up to speed, the series winding is cut out in order to obtain higher speed.

Differential Compound motors are seldom used. If, however, it is desired to have the speed remain more nearly constant than can be had from a shunt motor, or to have an actual increase in speed as the load comes on, then the series field should be connected differentially.

---

*Turning effort.

DIRECT CURRENT MOTOR APPLICATIONS

SUMMARY.

Type of Motor.	Speed Characteristics.	Use	Character of Load.
Series.	Variable Speed. High speed at light loads. Low speed at heavy loads.	Street cars. Cranes. Hoists. Small fans.	Requires large starting torque at low speed. Frequent starting and stopping. Load always connected.
Shunt.	Practically Constant Speed. Easy control of speed by field resistance or multi-voltage method.	All machine tools. Wood working tools. General motor applications.	Constant or adjustable speed. Light load start. Infrequent starting and stopping.
Compound (accumulative).	Practically Constant Speed. Easy control of speed.	Elevators. Punches. Shears.	Requires large starting torque. Uniform speed with sudden changes in load.
Compound (differential).	Can be made constant speed or with speed in-decreasing with load.	Seldom used.	One requiring more nearly constant speed than given by shunt or compound.

Current Required by Motors. As previously stated, the amount of current taken by a motor, at any time, depends upon the load placed upon it, that is, the work it is doing.

When a motor is running idle, of course it takes some power to run it, and, as there is no output, all of the power supplied to the motor must be lost in the motor. In other words, the power input into a motor running without load supplies the losses of the motor, under those conditions. The losses in the motor are principally bearing and brush friction, a little I_2R loss in armature and fields, and a small amount of power lost in Hysteresis and Eddy currents in the iron cores of armature and field. The amount of power required to run a motor without load will not be greater than from 5 to 10 per cent of its rating. That is to say, a 10 h. p. motor will take, at no load, from $\frac{1}{2}$ to 1 h. p. Large motors take the lower and small motors the higher percentage.

It is very often necessary to know closely the current that would be required at full load for a certain size of motor. This can be calculated approximately as explained below.

As stated previously, the horse-power rating of a motor is its full-load output, and, in order to calculate the corresponding current input, we must have an approximate value of the motor's efficiency and know the voltage for which the motor is intended. These values are usually known, excepting the efficiency. The efficiency can be closely approximated from later statements on efficiencies of motors. Knowing these values, then, to determine the full load-current, proceed as follows:

Watts Output = Horse power rating × 746.

Watts Input = Watts Output ÷ Efficiency.

Current Input = Watts Input ÷ Voltage.

For example, consider a motor rated at 10 horse-power, 115 volts.

Watts Output at full load } = 10 × 746 = 7460.

Watts Input = 7460 ÷ .85 (estimated efficiency).
= 8770 watts.

Current Input at full load } = 8770 ÷ 115.
= 76. amperes.

Rating of Motors. Motors are always rated in full-load, horse-power output. If a motor is rated as 25 horse-power, that means that the motor will deliver 25 h. p. continuously without over-heating, if operated under the conditions for which it was designed. The last point must be understood. Most motors are intended to be run as open motors, so that they will be well ventilated. If the above motor were to be enclosed so as to prevent free ventilation it would be able to carry possibly not more than 10 h. p. without over-heating. In other words, it would burn out if run at 25 h. p. output continuously.

Motors are designed to run open, or semi-enclosed, or fully enclosed, but the same motor has different ratings accordingly; thus, a certain motor is rated at 20 h. p. open and 8 h. p. fully enclosed.

Interpole Motors. As previously mentioned, the rating of a motor is determined largely by temperature rise, but to some extent, in the past, it was by sparking at the brushes. The last point is no longer of much importance because it is now possible to practically eliminate sparking at the brushes by using interpoles or commutating poles. These are small auxiliary poles, placed between the main poles as shown in Figure 6. These poles are connected in series with the line, so that as the load increases they supply an increasing flux to be cut by the coils under the brushes, thus preventing sparking as the load changes. By the use of interpoles and small fans on the armature of the motors, the rating of a motor of given weight and dimensions has been greatly increased in the last few years.

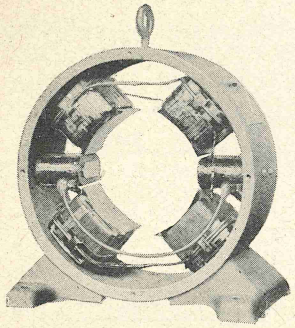


Figure 6—Inter-Pole Motor

Reversing Motors. As will be understood from the statements previously made, the direction of motion of a conductor depends upon the relative direction of the current in the conductor and the magnetism of the poles. Therefore, as might be expected, **the direction of rotation of a motor can be reversed by reversing either the current in the armature or the current in the field windings.** If the motor is a compound motor care must be taken to reverse both shunt and series field currents, in order to have them work together.

Reversing the line connections will not reverse the direction of rotation, because both armature and field current are reversed and therefore they have the same relation to each other.

Motor Starters. Full line voltage cannot be applied directly to a motor armature until the motor is up to full speed. The reason for this is, as stated before, that the resistance of the armature is very small, only a fraction of an ohm. Consider a 10 horse-power 115 volt motor with an armature resistance of 0.15 ohm. At stand-still, no counter E. M. F. is generated and, if the full voltage of the line were applied then, an enormous current would flow, as can be determined by applying Ohm's Law.

$$I = \frac{E}{R}$$

$$I = \frac{115}{0.15} = 770. \text{ amperes.}$$

The full-load current of the motor is only 80 amperes, so that 770 amperes would, of course, do much damage if the motor circuit were not properly protected by fuses or circuit-breakers. In order to keep the starting current down to a reasonable value, such as full-load current or 1.5 times full-load current, a resistance is connected in series with the armature at the time of starting. The amount of resistance required is comparatively small, as can be seen from this calculation.

Line voltage 115.

Full-load current 80 amperes.

Resistance of armature = 0.15 ohms.

Resistance required then in rheostat is.

$$R\text{ (rheostat)} + R\text{ (armature)} = \frac{E}{I} = \frac{115}{80} = 1.45 \text{ ohms.}$$

$$\begin{aligned} R\text{ (rheostat)} &= \text{total} - R\text{ (armature)} \\ &= 1.45 - 0.15 \\ &= 1.3 \text{ ohms.} \end{aligned}$$

Thus, the resistance required in the rheostat to keep the current down to normal value would not be greater than 1.3 ohms, with wire large enough to carry 80 amperes.

With this total resistance in the armature circuit and full voltage on the shunt field, enough current will flow through the armature to cause it to revolve. As soon as the armature is turning, its conductors are cutting lines of force and a counter E. M. F. is generated and the current input decreases as the speed increases. Some of the rheostat resistance can then be cut out, allowing the current to increase again, thus again increasing the speed and the counter E. M. F. This process continues until all of the resistance is cut out and the armature has full voltage applied to it, and is running at full speed. In con-

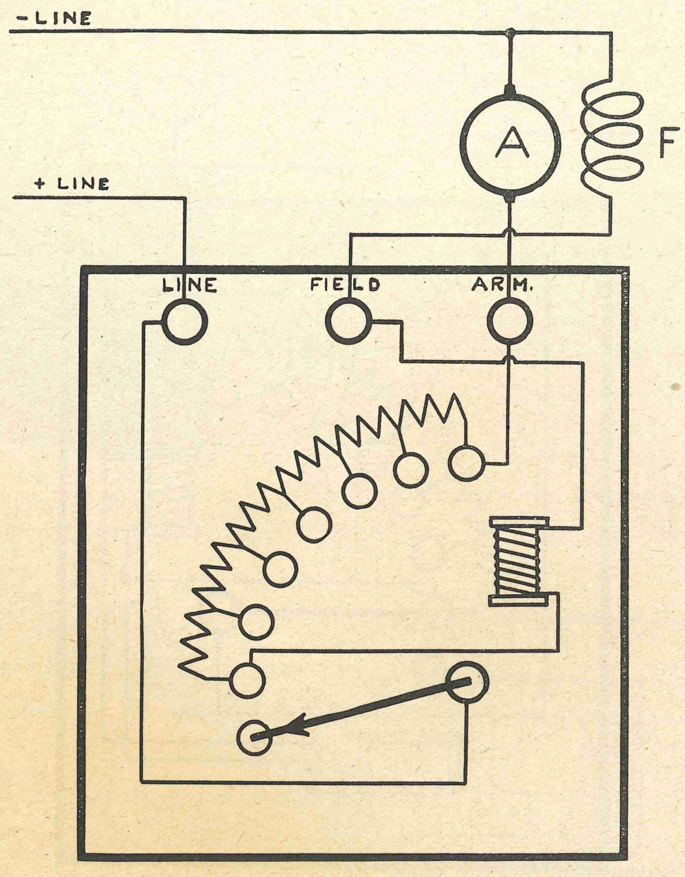


Figure 7—Diagram of Motor Starter with No-Voltage Release, Showing Motor Connections.

necting up shunt and compound motors two points must be kept in mind: **Always have full voltage on the shunt field** and **resistance in series with the armature on starting.**

For series motors always start with resistance in series with armature and field.

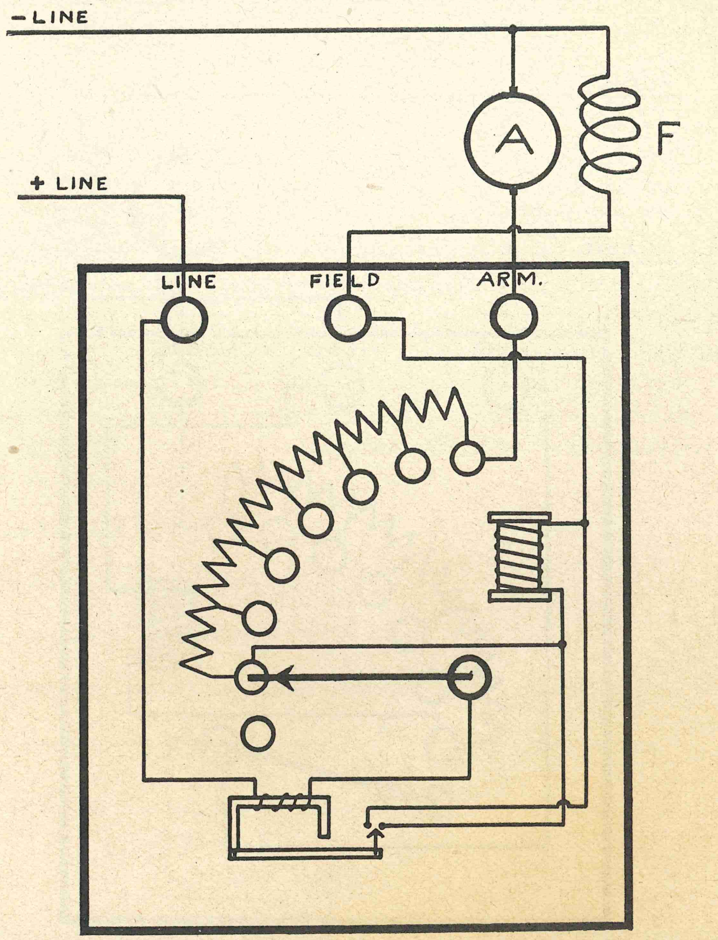


Figure 9—Motor Starter, with No-Voltage and Over-Load Releases

Suppose that, while the motor is running, the supply of current should accidently be cut off. The motor would then stop, leaving the rheostat with all of the resistance cut out. As soon as the supply would be thrown on, there would be an enormous rush of current through the armature, as explained before, unless some provision were made for returning the rheostat to the starting condition whenever the supply of current were shut off. This is accomplished by a device known as **the no-voltage Release.** Referring to Figures 7 and 8, 9 and 10, it will be seen that this is simply a magnet, connected in the shunt field circuit (or connected directly across the line), so that when the supply is shut off a spring returns the handle of the rheostat to the starting position. In this way, no harm can be done to the motor.

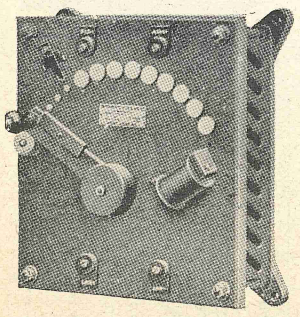


Figure 8—Small Motor Starter

Another protective device is often added; that is, an over-load release. This is an electro-magnet as shown in Figure 9. When the current reaches a predetermined high value, the keeper of the magnet is attracted and the no-voltage coil is short-circuited, thus killing the magnetism and allowing the spring to return the handle of the rheostat to the starting position.

Starters for Series Motors. Series motors are started in practically the same way as shunt and compound, except that the connections are slightly different, as shown in Figure 10.

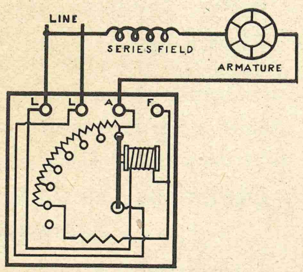
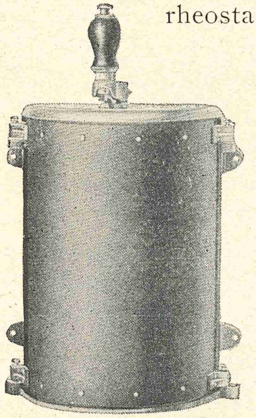


Figure 10—Starter Suitable for Series, Shunt or Compound Motors

Starters for Large Motors. All motors, both large and small, are started as already described. The starting rheostats for large motors are usually called controllers and have the contact drum separate from the resistance grids, as illustrated in Figure 11.

The resistance grids may be placed in any convenient place.



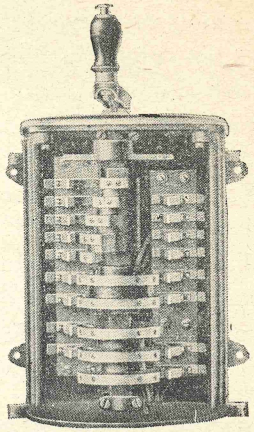


Figure 11—Drum Type Controller or Starter

Automatic Rheostats Many rheostats are made for remote control and are called automatic rheostats, because all that is necessary is to close the main switch and electro-magnets operate switches so as to cut out the starting resistance gradually. Such a rheostat is shown in Figure 12.

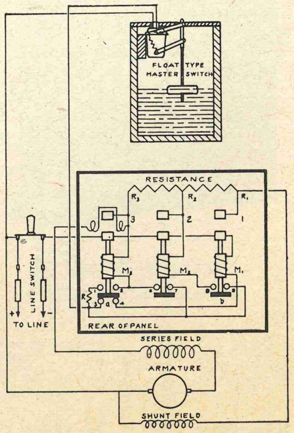


Figure 12—Automatic Rheostat Applied to Pump Motor

Definitions In working motor problems an understanding of the following definitions will be found very useful:

WORK is force acting through distance. The unit of work is the foot-pound and is the work done in moving a weight of one pound a distance of one foot.

POWER is the rate of doing work.

HORSE-POWER is doing work at the rate of 550 foot-lbs. per second or 33,000 foot-lbs. per minute.

1 Horse-Power = 746 Watts.

To convert horse-power to watts, multiply horse-power by 746.

$$\text{Watts} = \text{H. P.} \times 746.$$

To convert watts to horse-power, divide watts by 746.

$$\text{H. P.} = \text{Watts} \div 746.$$

Torque. There is one term that is very much used in motor work and that should be fully understood by the student; that is the word **TORQUE. TORQUE MEANS TURNING EFFORT.** Actual turning or speed does not enter into consideration. A little study of Figure 13 will explain this point. This represents a shaft having a turning effort or torque produced by the weight at the end of the lever arm. The arrow indicates the direction of motor torque required to hold, or raise the weight. Torque is expressed in **POUND-FEET,** the product of the weight (or force acting) by the length of arm on which it acts. In the case of a motor with a belt drive, it is the pounds pull on the belt bultiplied by the radius of the pulley in feet.

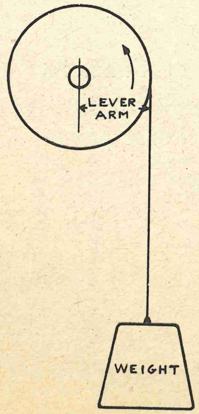


Figure 13—Torque

The output of a motor depends upon two things, namely; the torque exerted and the speed. The equation then for the output of a motor under test, by the use of a prony brake, as described later, is:

$$\left.\begin{array}{c}\text{Horse power}\\ \text{Output}\end{array}\right\} = \frac{\text{Weight} \times \text{Lever Arm (in feet)} \times 2\pi \times \text{Revolutions per minute}}{33{,}000}$$

Explanation:

Radius of pulley (in feet) $\times 2\pi$[*] = Circumference of pulley in feet or distance traveled in one revolution.

Lever-arm $\times 2\pi \times$ r. p. m. = Distance (in feet) traveled per minute.

Weight $\times$ Feet per minute = Foot-lbs. of work done per minute.

Work at the rate of 33,000 foot-lbs. per minute = 1 horse-power therefore Total Foot-lbs. per minute $\div$ 33,000 = Horse-power.

In the brake test referred to (see page 20), suppose that the net weight on the scales is 60 lbs. and the speed of the motor is 1,000 revolutions per minute and the center of the pulley to the point of pressure on the scales is 2 feet, the output is then

$$\text{H. P.} = \frac{60 \times 2 \times 2\pi \times 1000}{33000} = 23.$$

Consider the following problem:

A motor rated at 10 horse-power at 1000 revolutions, has a pulley 5″ in diameter. Find the total pounds pull on the belt when delivering full load. The equation for horse-power is

$$\text{H. F.} = \frac{\text{Pounds} \times \text{Radius of pulley} \times 2\pi \times 1000}{33000}$$

Solve for pounds:

$$\text{Pounds} = \frac{\text{Horse power} \times 33000}{\text{Radius} \times 2\pi \times 1000}$$

$$= \frac{10 \times 33000 \times 12}{2.5 \times 2 \times 3.1416 \times 1000} = \frac{3960000}{15700}$$

$$= 252 \text{ lbs.}$$

If a double ply belt is used and 50 lbs. pull per inch width is allowed, then a 5″ belt would be required. This, of course, does not allow for belt slip, which would require either a little wider belt or a slightly greater pounds-pull-per-inch width of belt.

---

[*] $\pi = 3.1416$.

Efficiency of Motors. In every conversion of energy there is some loss of energy, and that loss appears often as heat. That is the case in a motor. Energy is lost in the motor in Bearing friction, Brush friction, Windage, I^2R loss in the windings, Hysteresis, and Eddy current losses in the iron cores of armature and fields.

In small motors these losses are larger in proportion to the motor capacity than in large motors, that is, small motors are less efficient than large motors, as might be expected.

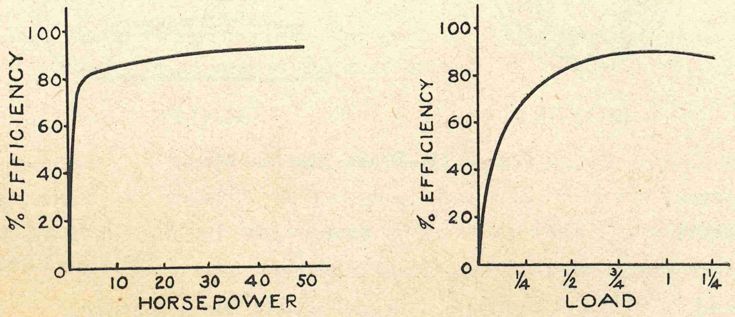
A very general definition of efficiency is the following:

Efficiency is the ratio of the output of a piece of apparatus to the input. Thus for a motor

$$\text{Efficiency} = \frac{\text{Horse power output}}{\text{Horse power input}}$$

$$\text{or Efficiency} = \frac{\text{Watts output}}{\text{Watts input}}$$

A curve of approximate full-load efficiencies of motors of various sizes is given in Figure 14.



Relation of Efficiency to Size of Motor.

Relation of Efficiency to Load.

Figure 14—Typical Efficiency Curves

The efficiency also varies with the load. As previously stated, when a motor is running light all of the power supplied to it is lost; in other words, the efficiency is zero, while, at full load, only a part of the energy is lost, meaning higher efficiency.

The general form of efficiency curve is also shown in Figure 14. This curve shows low efficiencies for small loads, rapidly increasing as the load increases, with a maximum value of efficiency at or near full-load. The efficiency of a motor and the point of maximum efficiency are practically controlled by the designer, except, of course, that there are well-defined upper limits of efficiency which cannot be exceeded.

Efficiency Test. Small motors can be tested by actually loading and measuring input and output. The input would be measured by ammeter and voltmeter, while the output would be measured by means of a prony brake shown in Figure 15 and calculated as explained on page 18.

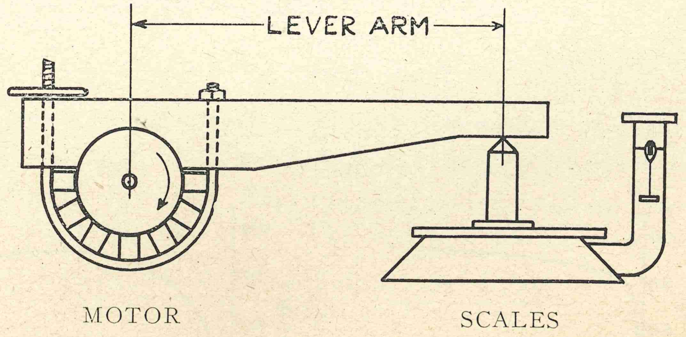


Figure 15—Brake Test on Motor

Factors Determining Speed. The speed of a motor can be increased or decreased in several ways, namely:

1. Changing voltage across the armature.
2. Changing current in the field.
3. Changing reluctance of the magnetic circuit.

The reader will remember that the counter E. M. F. of a motor is almost equal to the applied voltage and must remain so. If the applied voltage is raised, more current will flow in the armature; more torque is developed, the load being unchanged; the speed will increase until the counter E. M. F. is

again almost equal to the applied voltage, or, in other words, until the armature current is reduced to the amount required to produce the required torque.

If the field magnetism is weakened, the armature must run faster to generate the same counter E. M. F. as before.

If the field is strengthened, it must run more slowly.

Methods of Speed Control. The greatest advantage of direct current motors over alternating current motors is that the speed of direct current motors can be controlled easily over a wide range. The principal methods of speed control are the following:

Armature-resistance method.

Field-resistance method.

Magnetic-reluctance method.

Multi-voltage method.

Ward-Leonard method.

Only a few of these have extensive application. These apply principally to shunt and compound motors.

Armature Resistance Method of Speed Control. In the armature resistance method, a rheostat capable of carrying full-load current continuously is connected in series with the armature. The field current is not varied. Motor connections are made as shown in Figure 16.

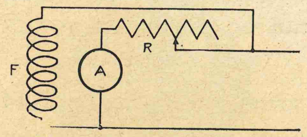


Figure 16—Armature Resistance Method

The range of speed for this method is from zero to normal speed, i. e., the speed of the motor with normal voltage on armature and field. This method is not commonly used because it is very wasteful of energy. At half speed, for example, the voltage across the armature must be reduced to practically one-half, which means that as much power would be wasted in the resistance as would be used in the motor as represented in Figure 16. Another serious disadvantage is that the speed changes greatly with change of load. Thus, if in the case just mentioned where the motor was running at half speed, the load should be reduced 50 per cent. then the speed would increase to about 75 per cent. of normal.

The **Uses** of this method are mostly of an emergency character or as an intermediate method of speed control to be used with some other method.

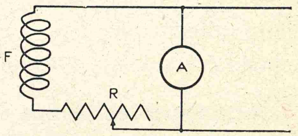


Figure 17—Field Resistance Method

Field Resistance Method. This method uses a variable resistance in the shunt field circuit. The first cost is low, range of speed large, as high as 3 or 6 to 1, that is, the highest speed is from 3 to 6 times the lowest; the loss of power is only a fraction of one per cent. This method is probably the most generally used for motor application where a wide range of speed is required. A diagram of connections is shown in Figure 17.

Upper Speed Limit. In applying methods of speed control to motors, the question usually arises as to how fast the motor can be run without danger of wrecking it. If the armature is well constructed, as all standard motors are, the maximum rotative speed allowable is a speed corresponding to a peripheral speed of 5,000 feet per minute. That is to say, a point on the outside of the armature cannot travel much faster than 5,000 feet per minute, without danger to the armature. The peripheral speed of the armature can be calculated as follows:

Peripheral speed = Diameter of the armature in feet × 3.14 × revolutions per minute. For example, given a motor having an armature 15″ in diameter, to find the maximum permissible rotative speed:

$$\text{Circumference of armature in feet} = \frac{15 \times 3.14}{12} = 3.9 \text{ feet}$$

i. e., in one revolution, a point on the outside of the armature would travel 3.9 feet.

Find the number of revolutions corresponding to 5,000 feet per minute.

$$\text{r. p. m.} = \frac{5000}{3.9} = 1280$$

This, then, would be the upper safe limit of speed.

Some motors are designed so that their normal speed is close to the maximum, and therefore it is not possible to increase their speed to any extent by using the field rheostat method of speed control. Motors desired for wide range of speed should be selected especially for that purpose, as the manufacturers build motors especially designed for adjustable speed work.

Magnetic Reluctance Method This method is a mechanical method of speed control and consists in changing the length of air-gap between the pole faces and the armature. The method is represented diagrammatically in Figure 18,. A photograph of such a motor built by the Stow Electric Motor Co., of Binghamton, New York, is shown in Figure 19.

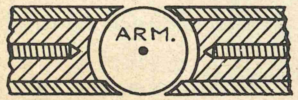


Figure 18—Reluctance Method

This method gives a little greater range of speed than the field resistance method, as the sparking limit of the machine is not reached so soon. It has the disadvantage of requiring a special motor; that is, it is not applicable to the standard motors, as are the other methods.

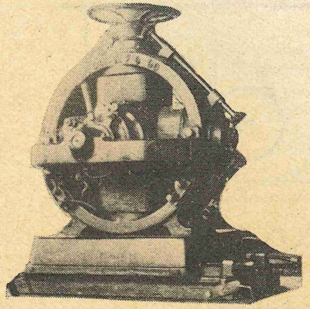


Figure 19—Stow Adjustable Speed Motor

Multi-Voltage Method. The multi-voltage method, as the name implies, has several voltages that can be applied to the motor armature while the field is supplied with constant voltage. The general scheme is represented in Figure 20. This method has the same range of speed and the same characteristics as the armature resistance method, but has the decided advantage of lower power loss. The greatest disadvantage of the method is that it requires a supply of several different voltages and a large amount of wiring. A decade ago it was generally considered an almost ideal system for large machine shops. Since then, the advances in motor design have enabled the field resistance method to meet practically all requirements.

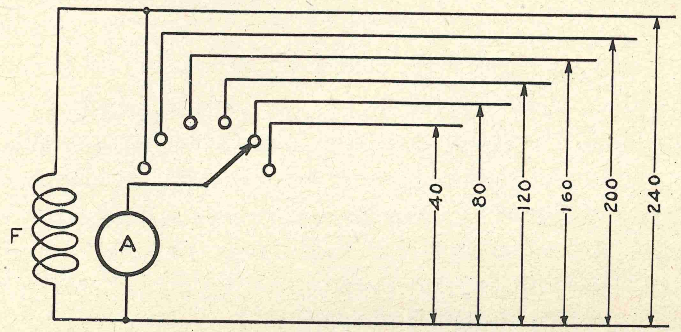


Figure 20—Multi-Voltage Method

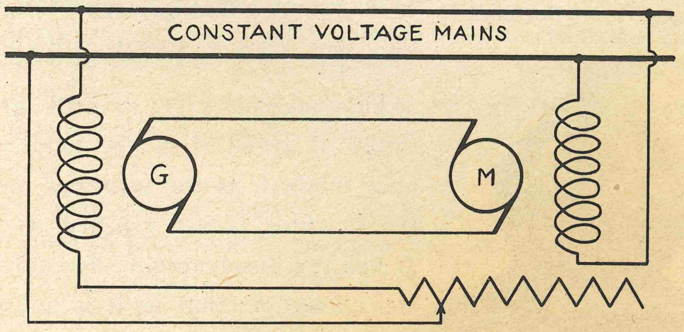


Figure 21—Ward-Leonard System

Ward-Leonard System. The Ward-Leonard is a method of speed control applicable to very large motors, such as for mine-hoists, and to smaller motors, where first cost is of little importance compared with the value of excellent control. It consists of a separate constant-speed generator for each motor, with the voltage of the generator, and therefore with the voltage supplied to the motor armature under perfect control of the motor operator. The simplified diagram of such a system is shown in Figure 21.

It can be seen that this method is not feasible for general application. It is used for mine-hoists, and for turret motors on battleships, testing work, and for similar uses.

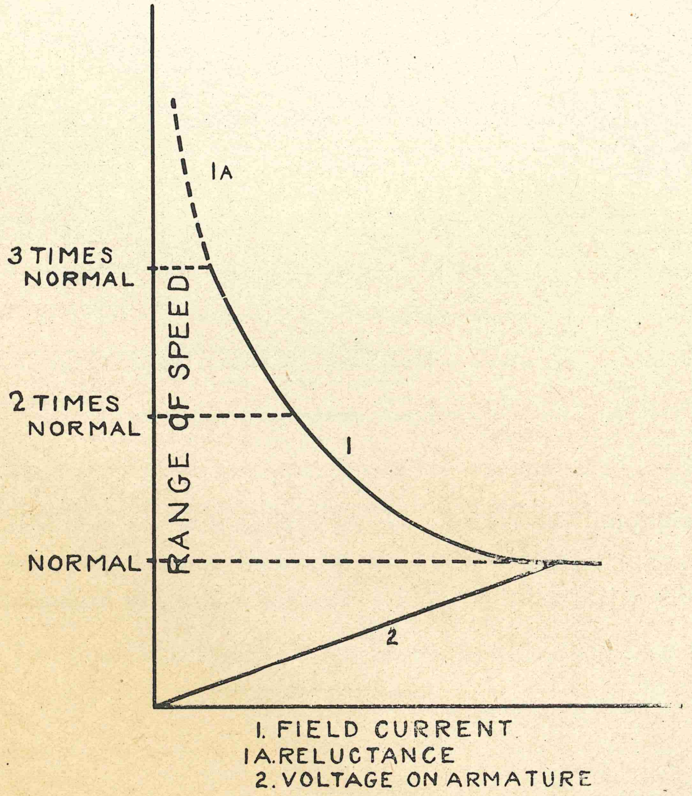


Figure 22—Curves of Speed Control

Figure 22 represents graphically the range of speed obtained by the different methods of speed control.

The following table gives a summary of the facts regarding the methods of speed control:

METHODS OF SPEED CONTROL

SUMMARY

Shunt and Compound Motors.

Method.	Range of Speed.	Application.	Advantages.	Disadvantages.
Armature Resistance.	Zero to normal.	For securing low speeds. Emergency control.	Low first cost. Simplicity.	Large loss of power. Poor speed regulation.
Field Resistance.	Normal to six times normal with possible range of thirty times normal by special design.	Machine tools and all applications where wide speed range is desirable.	Low first cost. Small loss of power. Good speed regulation. Easy control of speed.	None.
Reluctance.	About the same as field resistance method.	As above. Not widely used.	Small loss of power. Good speed regulation.	Mechanical control. Special consruction.
Multi-voltage.	Zero to normal. Combined with field rheostat method so as to give from zero to six times normal.	Large Machine shops.	Wide range. Easy control.	High first cost.
Ward-Leonard.	Same as above.	Mine hoists. Turrets of battleships. Rolls in steel mills.	Perfect control of speed.	High first cost. Separate generator for each motor.

Conclusion. The student should realize that the material presented in this lesson is of great importance and should be learned thoroughly. **Re-read** and **study it carefully.**

DEMONSTRATIONS FOR LESSON IV.

Class leaders are urged to make these demonstrations as complete as possible, because in almost no other way can these fundamental principles be so effectively impressed on the student's mind.

Have a small shunt motor with a field rheostat, starting box, voltmeter, and ammeter for armature and field circuits.

The following points can be demonstrated:

1. Connection for a shunt motor.

2. Construction and use of starting rheostats.

3. Effect of change of voltage on the armature, and on the speed.

4. Effect of change of field current on the speed.

5. Reversal of direction of rotation of motor by reversing armature connections.

6. Same effect by reversing field connections.

7. Effect of reversing line connections.

8. Amount of power required to drive the motor at no load as compared to amount required for full load.

9. Effect on current input, by loading the motor. (Hold a board against the pulley.)

10. If possible, measure the resistance of armature and field to fix these points in the student's mind.

REFERENCE BOOKS.

Electricity Experimentally and Practically Applied, by Sidney W. Ashe, D. Van Nostrand Co., New York.

Applied Electricity for Practical Men, by Arthur J. Rowland, McGraw-Hill Book Co., New York.

Elements of Electricity and Magnetism, by Franklin and McNutt, McMillan Co., New York.

Elements of Electricity, by Timbie, McMillan Co., New York.

Elements of Electricity and Magnetism, by D. C. and Wm. B. Jackson, McMillan Co., New York.

N. E. L. A.—Salesman's Handbook. Power section.

QUESTIONS

Note: These questions are to be answered after the lesson has been studied carefully, and without further reference to the lesson.

1. Explain fully the difference between a generator and a motor.

2. Discuss motor action and its dependence upon Counter-Electro-Motive Force.

3. Draw simple diagram of Connections for Series, Shunt and Compound motors.

4. Draw and explain the meaning of the characteristic curves of Series, Shunt and Compound motors.

5. State clearly the application for which each type of motor is best suited.

6. Discuss fully the field rheostat method of speed control. Why is it most generally used?

7. Explain why a starting rheostat is necessary.

8. If the full load current of a 115 volt motor is 100 amperes and the armature resistance is 0.1 ohm, what resistance is necessary in the starting rheostat?

9. If a motor takes 40 amperes at 230 volts, what is the approximate output of the motor in horse power? Give your calculation.

10. A 230 volt motor is delivering 15 horse power. Calculate the approximate current taken by the motor.

INDEX

Page
Counter-Electro-Motive Force 4
Definition of Electric Motor 3
Definitions 16
Efficiency Test 20
Electric Motor, Definition of 3
Motor, Compound 7
  " Series 6
  " Shunt 6
  " Starters 12
Motors, Efficiency of 19
  " Interpole 11
  " Rating of 10
Speed Control, Methods of 21
Torque 17

NOTICE.

Special sheets for answers to test questions have been sent to you. These answers should be sent to the Chairman within 30 days. They will be corrected, graded and returned to you direct or through your class leader.

Certificates will be granted to those obtaining an average grade of 70 per cent or over.

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LESSON VIII—INDICATING MEASURING INSTRUMENTS

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INTRODUCTION

Indicating measuring instruments are so generally used that every student should be familiar with the general types of instruments and their principles of operation.

NATIONAL ELECTRIC LIGHT ASSOCIATION COURSE IN PRACTICAL ELECTRICITY.

LESSON VIII—INDICATING MEASURING INSTRUMENTS.

Measurement of Electrical Quantities. The measurement of electrical quantities is very peculiar, inasmuch as we cannot measure electricity itself. All electrical measurements are measurements of effects produced by electricity, such as **chemical effect, heating effect** or **magnetic effect.**

If direct current flows through a solution of some metal, the metal will be deposited out of the solution onto one of the electrodes. The amount of metal deposited will depend upon the number of amperes and the length of time. This is a **chemical effect** and can be used to measure current.

When current flows through a conductor heat is generated in the conductor proportional to I^2R. When heated the metal expands. The amount of this expansion can be measured, giving an indirect measurement of the current flowing, by the **heating effect.**

When current flows through a wire, a magetic field is set up about the wire. The strength of this magnetic field is proportional, in a coil, to the number of ampere turns of the coil. The amount of magnetism, and therefore, indirectly the current, can be measured by measuring the pull of the magnetic field on an iron core. This is how current is measured by its **magnetic effect.**

Instruments working on magnetic principles are most commonly used.

Quantities to Be Measured. The electrical quantities which are most commonly measured are:

Current, in Amperes
Pressure, in Volts
Power, in Watts

and in addition in an alternating current circuit:

Frequency, in Cycles per second.
Power factor, in per cent.

Classification of Instruments. Measuring instruments are classified in many different ways, according to use, as **Ammeters, Voltmeters, Wattmeters,** etc., or according to the principle on which they operate as **magnetic vane type, electro-dynamometer type, hot-wire type,** or according to the kind of service they are suited for, as **direct-current instruments** or **alternating-current instruments.**

This lesson is concerned cheifly with the fundamental principles of construction and operation of the most generally used types of instruments.

Ammeters and Voltmeters. The same identical types of instruments are used both as ammeters and voltmeters.

The purpose of the **ammeter** is to measure the current flowing in a conductor; that is, it is an instrument to be connected in series with the circuit as shown in Figure 1. If it is to measure the flow of current, it must not change the value of the current by being inserted in the circuit. This means that an ammeter must have a very low resistance, always a very small fraction of an ohm.

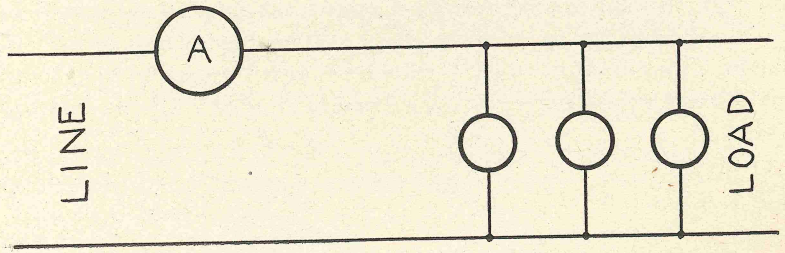

Figure 1—Ammeter Connection

The purpose of a **voltmeter** is to measure the voltage or pressure between two points, as A and B of Figure 2, or the voltage between the mains, as from A to C. Connecting the voltmeter must not change the voltage of the circuit, therefore the voltmeter itself must take very little current. In other words, it must have a very high resistance, usually about 100 ohms per volt; that is, a voltmeter reading to 150 volts would have a resistance of something like 15,000 ohms. High resistance is also very desirable because the voltmeter, if a station or substation instrument, will be connected to the circuit all of the time, and the power required to operate it is then almost negligible.

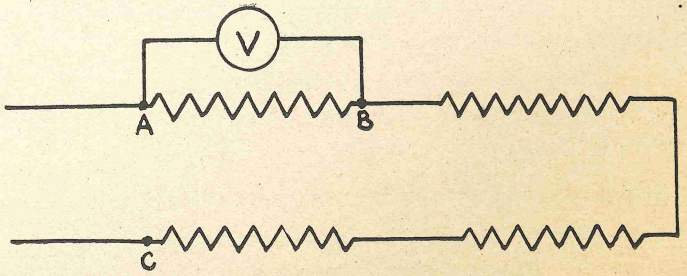

Figure 2—Voltmeter Connection

Plunger Type Instruments. Early instruments were of the **plunger-type** and consisted of a coil through which the current passed and an iron core connected to a pointer as illustrated in Figure 3. The greater the current the stronger the magnetic field and the farther down the core is drawn, resulting in a greater deflection of the pointer or needle. With a given sized core and arrangement of pointer and weights, a certain number of ampere turns on the coil will give a full scale deflection. If the instrument is made to measure small currents it has a coil made up of small wire and a large number of turns, whereas, if it is made to measure large currents, the coil is made up of a few turns of large wire. The instrument in Figure 3 is a 60-ampere instrument.

If this type of instrument is to be used as a voltmeter, the coil is made of a very large number of turns of very small wire, having such a resistance that when the coil is connected to the full voltage, the number of ampere turns will be the number required to give a full scale deflection. For example, the instrument shown in Figure 3 has 15 turns of wire to give a full scale deflection with 60 amperes, that is 900 ampere turns are required. This same instrument could be used as an ammeter, to measure 5 amperes by using a coil of 180 turns. It could be used as a voltmeter for 150 volts, if the coil was wound with 45,000 turns and 7,500 ohms resistance. The current would then be 0.02 of an ampere, and the ampere turns would be 0.02 × 45,000, or 900.

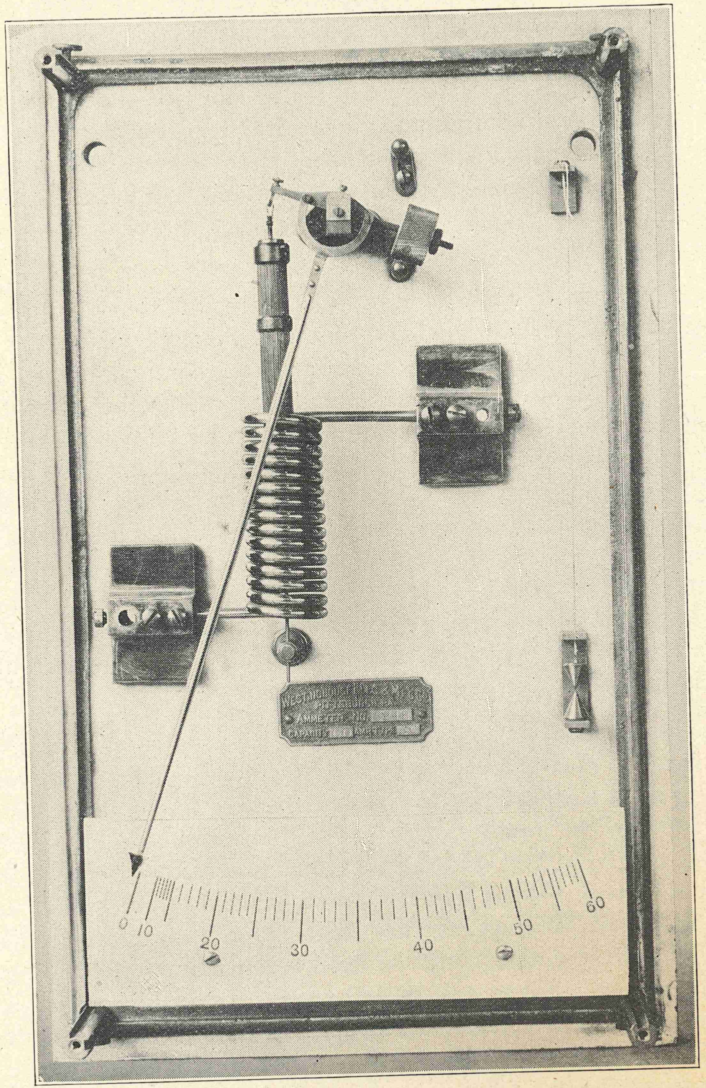

Figure 3—An Early Plunger Type Ammeter

Magnetic Vane Type. An instrument operating on somewhat the same principle is the modern **magnetic vane** instrument. This instrument consists of an inclined coil, which carries the current, having a shaft carrying one or more inclined soft iron vanes. These vanes are not parallel to the direction of the lines of force when the pointer is at the zero position. As current passes through the coil the magnetism tends to pull the vanes into a position parallel to the lines of force, thus moving the needle across the scale. Figure 4 illustrates this type of ammeter as made by the General Electric Co. The coil can be wound for any desired current. This instrument is primarily an alternating current instrument, the vane being small and of soft iron so as to have little hysteresis loss, but can be used on direct current with good results if the average of two reversed readings be taken.

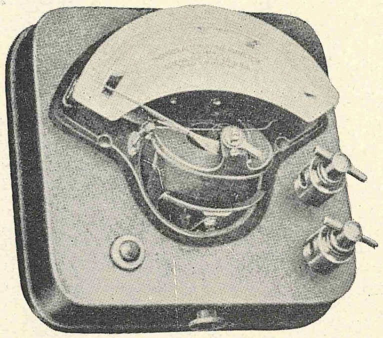

Figure 4—An Ammeter of the Magnetic Vane Type

D'Arsonval Type. Another type of instrument that is very generally used for direct currents is the **D'Arsonval** or galvanometer type. It consists essentially of a permanent magnet field and a movable coil attached to the needle. Figure 5 shows the arrangement of the parts of this instrument. The movable coil is wound of very fine wire on a small aluminum rectangle and is supported by jewel bearings over a stationary iron core. The coil is connected to the outside circuit through very fine hair springs. When no current is passing through the coil, the springs return the needle to the zero position. When current passes through the coil there is a force acting to turn the coil to a position, such that the lines of force set up within the coil will become parallel with the lines of force of the permanent magnetic field. In order to have the instrument sensitive and accurate it is necessary to have the moving element of very light weight, and this necessitates the use of fine wire. Therefore the moving coil can carry only a very small current.

This type of instrument is used for both ammeters and voltmeters.

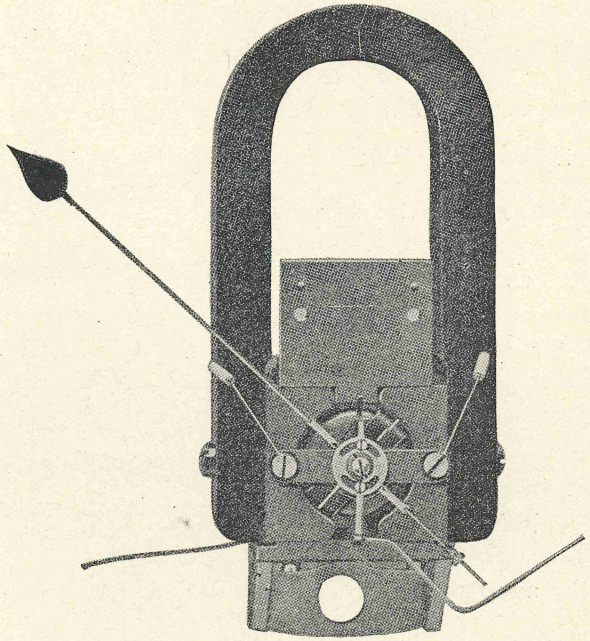

Figure 5—Mechanism of the D'Arsonval Type of Instrument—Weston

When used as an ammeter the larger part of the current passes through a shunt, as explained later. When used as a voltmeter the moving coil is connected to the circuit, through a very high resistance, so that when full voltage is applied, the proper current to give full scale deflection will pass through the moving coil.

Hot-Wire Instruments. An instrument less used, but one that can be used with equal accuracy, on both d-c. and a-c. circuits is the **hot-wire** instrument. The action of this instrument depends upon the heating and resulting elongation of a wire, through which current passes. One form of this type of instrument is arranged as shown in Figure 6.

A fine wire, **a-b,** extends from the cross-piece **c** around the drum **d** and back to an insulated segment on **c.** Current passing through the wire **a,** from **c** to the connection near **d,** heats and lengthens the wire **a.** The increased length of wire **a** is taken up by the spring **f,** thereby rotating the drum **d,** and moving the arm **g.** A thread wound around the pointer shaft **h,** and held in the bow causes the pointer **i** to move.

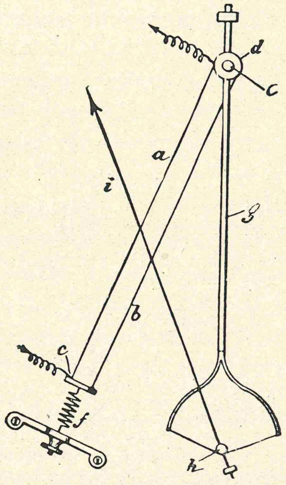

Figure 6 — Diagram of the Roller-Smith Co. Hot-Wire Type of Instrument

It will be seen that the heating effect is the same whether the current is direct or alternating and the instrument is therefore accurate on both. The wire to be heated is very small in diameter and can carry only a very small current. Unless the instrument is to be used as a milli-ammeter* it is provided with a shunt, as later described. The shunt can be made for any current and the instrument can be provided with any number of shunts.

The same type of instrument is used as a **voltmeter** by using a high resistance in series with the wire to be heated, in a manner similar to that described for the D'Arsonval or galvanometer type of instrument. Multipliers are used as discussed later.

Hot-wire instruments have an advantage that they give a steady reading at an average value when current or voltage fluctuates rapidly. Some types of hot-wire instruments have a disadvantage in that they require a zero adjustment on account of changes in room temperature.

Ammeter Shunts. When used as an ammeter, the instrument is always provided with a shunt, either within the instrument or as a separate part. An ammeter shunt is a definite low resistance connected in parallel with the instrument so that the main current divides in proper proportion between the shunt and the instrument. Figure 7 shows the arrangement of shunt and instrument. The resistance of shunt and instrument are so proportioned that the current divides between them in the proper definite proportion. For example, if the main line carried 10 amperes, 9.999 amperes might pass through the shunt and 0.001 of an ampere through the instrument. The current divides in inverse proportion to the resistances; that is, the shunt is of lower resistance and carries the larger current and the instrument is of higher resistance and carries the smaller current. Or it can be looked upon as a matter of voltage drop; that is, when the main circuit is carrying full current, there is sufficient voltage drop across the shunt to send the proper current through the instrument to give full scale deflection. The instrument is then marked to show the full current in the main circuit, although only a very small fraction of the full current passes through the instrument itself. The voltage drop across the shunt, and therefore the reading of the instrument, will always be proportional to the current passing through the main circuit. From this it will be seen that full scale deflection of the instrument is always obtained if the same low voltage is impressed upon it. Therefore, the same instrument can be used for any number of shunts having different ranges of current. If the resistance of the shunt is made twice as great, then the instrument will give the full scale deflection for one-half the value of current and the scale can be so marked or a multiplying factor used. Portable ammeters are often provided with several shunts, so that the same instrument can be used for the accurate reading of a wide range of currents. For example a given instrument has shunts for 1, 5, 10, 25, 50 and 100 amperes. With the proper shunt any one of these currents will give a full scale deflection on the instrument and 1 ampere can be read on the instrument just as accurately as can 100 amperes. The same general statements regarding shunts apply also to switchboard type instruments. Here, however, several shunts are not provided for the same instrument, but if the instrument is to be placed on a different circuit a new shunt can be provided and the scale recalibrated for any desired current. For example, an ammeter that was at one time used on a 10,000 ampere shunt is now used on a 10 ampere shunt, the instrument giving full deflection in both cases. A switchboard type of shunt is shown in Figure 8.

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*Ammeter to measure thousandths of an ampere.

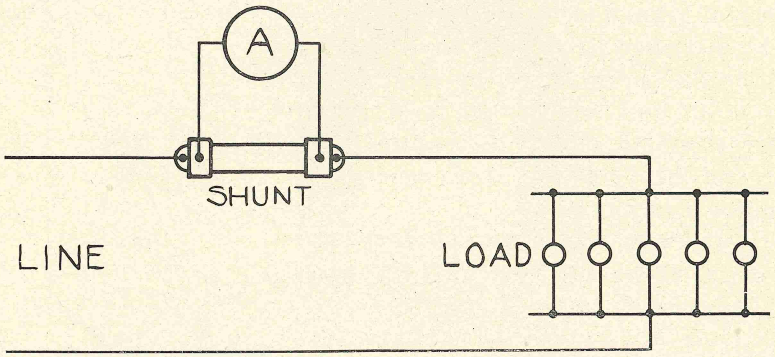

Figure 7—Diagram of Connections for an Ammeter with External Shunt

There is one precaution that must always be taken with shunt instruments and that is to see that the proper leads (wires) for connecting the instrument to the shunt are always used. The instrument is calibrated with certain connecting leads and if the length of these is changed or other leads used then a very appreciable error may be introduced. These connecting leads are always marked with the serial number of the instrument, so that they can be easily identified.

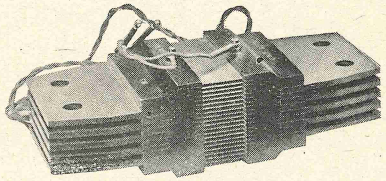

Figure 8—A Weston Switchboard Ammeter Shunt

In station and substation work it is often desirable to do away with the regular instrument shunt as it is rather difficult to install in a heavy bus-bar. In this case a portion of the bus-bar is used as the shunt. All that is necessary is to include between the instrument leads such a length of the bus-bar as will give the desired resistance. The greatest objection to this scheme is that, whereas the resistance of the regular shunts does not change appreciably with the temperature, the resistance of the bus-bar will. This can be compensated for by coiling the proper length of instrument lead and placing it against the bus, so that the resistance of the leads will increase in the same proportion as the bus, thus keeping the ratio of the shunt resistance to the instrument circuit the same.

Voltmeter Multipliers. The range of voltage on which a given voltmeter can be used can be increased by the use of a multiplier. A multiplier is simply a resistance, of proper value, connected in series with the voltmeter so that the voltmeter can be used on a higher voltage without carrying more than normal current. The resistance of the multiplier is always a multiple of the voltmeter resistance. For example, if a certain 150 voltmeter having a resistance of 13,200 ohms, is connected in series with an equal resistance to a 300 volt circuit, the current will not exceed the normal current for which the instrument was intended. The scale reading, however, must be multiplied by two since the combined resistance of the voltmeter and multiplier is twice that of the voltmeter itself. If a resistance three times the instrument resistance, that is, 13,200 × 3 or 39,600 ohms is connected in series with the voltmeter, the instrument with its multiplier can be used up to 600 volts and all readings will be multiplied by 4.

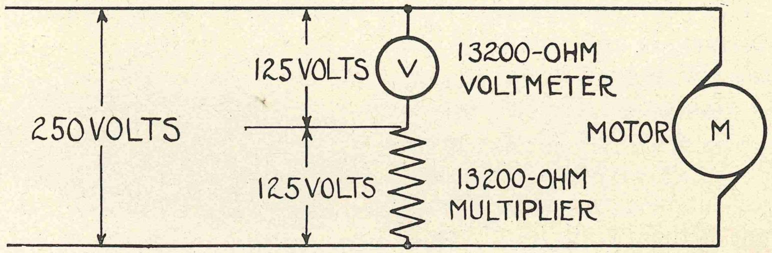
250 VOLTS
125 VOLTS
V
13200-OHM VOLTMETER
MOTOR
M
125 VOLTS
13200-OHM MULTIPLIER

Figure 9—Connection of a Voltmeter with Multiplier

A very convenient multiplier is to have a portable resistance provided with taps so that the same instrument can be used on 150, 300 or 600 volts. This arrangement is represented in Figure 10. One instrument with its multiplier will thus answer the purpose of three instruments at less than half the cost.

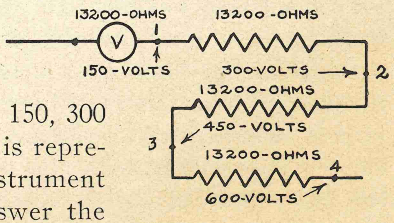
13200-OHMS
13200-OHMS
V
1
150-VOLTS
300-VOLTS
2
13200-OHMS
450-VOLTS
3
13200-OHMS
4
600-VOLTS

Figure 10—Voltmeter with Multiplier for Several Voltages.

Dynamometer-Type Instruments. A type of instrument, very accurate, and much used for both direct and alternating currents is the dynamometer type of instrument. This instrument consists of two sets of coils, one stationary and one movable. In the Siemens type of dynamometer, the coils are set at right angles to each other and arranged as represented in Figure 11. The coils are connected in series in both ammeter and voltmeter. When current is flowing in the coils there is a force acting that tends to turn the movable coil so that its lines of force will coincide with those of the fixed coil. This force acting between the coils is opposed by a torsion spring, connected to a milled head and pointer. Torsion is applied to this spring by turning the milled head until the movable coil is brought back to its zero position; that is, a position where its magnetic field is at right angles to that of the fixed coil. When this balance between the magnetic force and the spring is secured, the pointer indicates the reading of the instrument. An instrument of this type is shown in Figure 12.

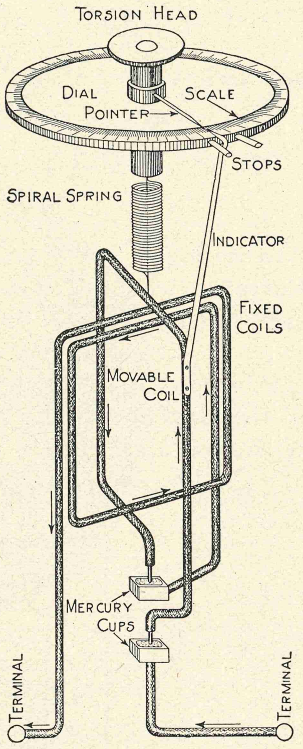
TORSION HEAD
DIAL
SCALE
POINTER
STOPS
SPIRAL SPRING
INDICATOR
FIXED COILS
MOVABLE COIL
MERCURY CUPS
TERMINAL
TERMINAL

Figure 11—Sketch of Siemens or Torsion Type of Dynamometer

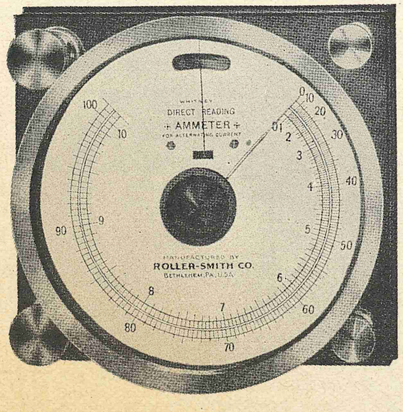
DIRECT READING
AMMETER
FOR ALTERNATING CURRENT
ROLLER-SMITH CO.
BETHLEHEM, PA. U.S.A.

Figure 12—A Torsion Type Ammeter Roller-Smith Co.

Many ammeters and voltmeters are made on the dynamometer principle, but do not have the torsion spring. In these instruments, the movable coil is attached to the pointer shaft and the coil and needle are deflected together against the action of small hair-springs. Figure 13 is a sketch of such an instrument.

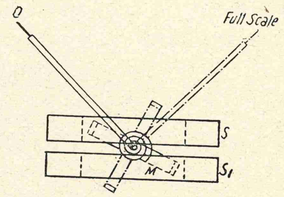

Figure 13—A Dynamometer Type of Instrument Without Torsion Spring

Alternating Current Instruments. As mentioned before, some of the instruments described can be used with equal accuracy on either direct or alternating current. There are, however, certain ammeters and voltmeters that can be used on alternating current only. These instruments are of the **induction type.** These instruments consist of a fixed coil wound on an iron core, and an aluminum cup or disk mounted on the needle shaft. Current passing through the coil sets up a moving magnetic field which cuts the metal cup or disk, setting up eddy-currents, producing a motor action or torque, proportional to the current passing through the instrument.

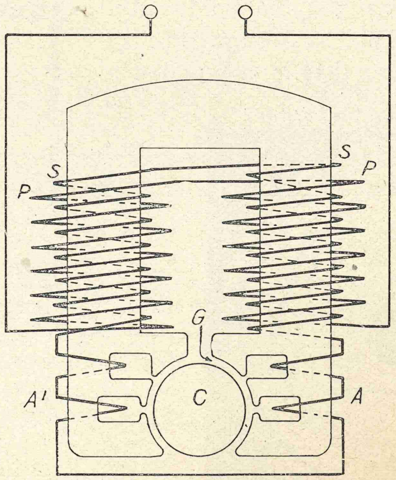

Figure 14—Sketch of an Induction Type Ammeter—Westinghouse

In the instrument represented in Figure 14 there is a transformer action between the primary coils P P and the secondary coils S S, and A^1 A, which results in a moving magnetic field cutting the aluminum cup C and producing a torque proportional to the current flowing through the winding P P.

A photograph of the mechanism of this instrument is shown in Figure 15.

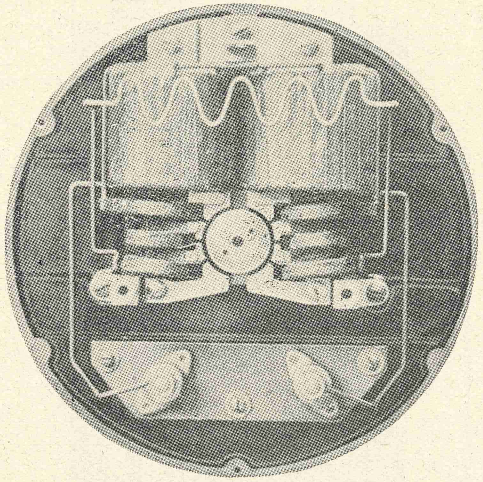

Figure 15—Induction Type Ammeter with Cover Pointer and Dial Removed—Westinghouse

Both ammeters and voltmeters are made in the induction type. This type of instrument is simple and rugged, although not as accurate as the dynamometer type.

Electrostatic Voltmeter. For very high voltage circuits, the electrostatic voltmeter is often used. As shown in Figure 16, this consists of two pans, each connected to one line of the high voltage circuit. These plates take on opposite electrostatic charges which causes a mutual attraction between the pans. The pan which is free to move is connected to the needle, thus producing a deflection proportional to the voltage applied.

Electrostatic voltmeters can be made for low voltages but this requires an instrument of rather complicated construction and other types are therefore to be preferred for low voltage work.

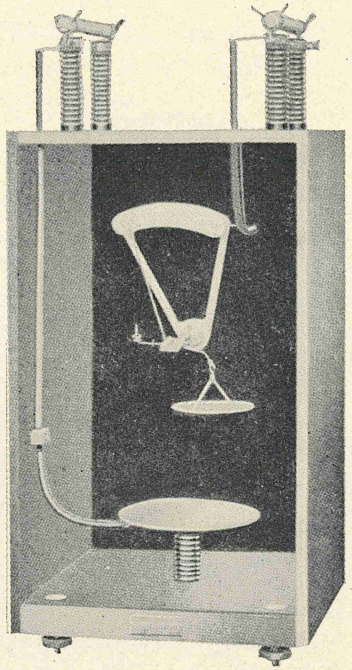

Figure 16—An Electrostatic Voltmeter
15,000 to 50,000 Volts—General Electric Co.

Wattmeter. In order to measure power an instrument must have its reading proportional to voltage multiplied by current times power factor, that is, its reading must at all times be proportional to the true watts in the circuit. This is obtained if the instrument is provided with two sets of actuating coils, one set producing a flux proportional to the current, in the circuit, and the other set producing a flux proportional to the voltage of the circuit, and the coils so arranged that they can produce together the torque for the indicating element of the instrument. The wattmeter is primarily an alternating current instrument.

The connections for an indicating wattmeter are shown in Figure 17. The current coil is connected in series with the line so as to carry the current, the same as an ammeter, and the voltage coil is connected directly across the line the same as the voltmeter.

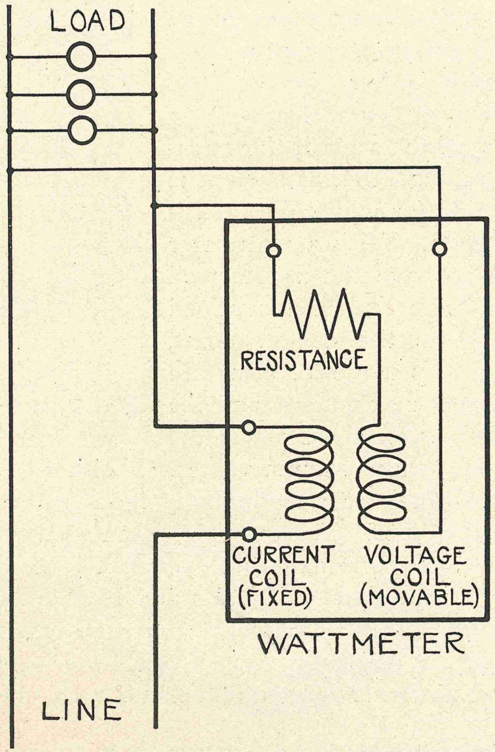

Figure 17—Diagram of Connection for a Wattmeter

One of the most satisfactory **indicating wattmeters** is of the **dynamometer type.** The coils are arranged exactly as described for the ammeter and voltmeter of this type on page 13, the fixed coil being the current coil and the movable coil the pressure coil. This is the preferable relation because the pressure coil carrying very small current can be made of very small wire, and therefore of light weight, giving a more sensitive instrument. A resistance is placed in the pressure coil circuit, so as to limit the current without making the coil too large. This instrument may use the same torsion head device with pointer attached as explained previously.

The most commonly used indicating wattmeters are constructed on exactly the same principle, except that the moving coil is mounted directly on the pointer shaft, which does away with the torsion-head device. This is shown in Figure 18.

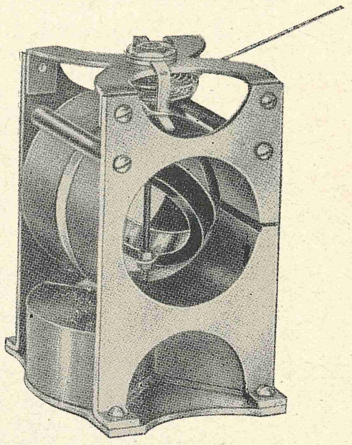

Figure 18—Mechanism of a Dynamometer Type Instrument. Roller-Smith Company

There are a few **precautions** to be observed with wattmeters that are not necessary with other instruments. With an ammeter or voltmeter the needle moves off the scale if the quantity passing through the instrument is greater than that for which the instrument is designed. With a wattmeter it is possible to have the needle well down on the scale and still overload the instrument to the danger point. Each instrument is made for a certain maximum current and voltage and the maximum reading on the scale is the product of these two maximum values. If either quantity is low then the other can be correspondingly high and the needle remain within the scale. For example, if an instrument is rated at 3,000 watts, 150 volts and 20 amperes, it is possible to have 75 volts and 40 amperes, or 20 volts and 150 amperes and have the needle within the scale but have the current coil overloaded to the burning out point. It is well, therefore, to always use a voltmeter and ammeter with a wattmeter as a check on these quantities.

On account of having both current and voltage connections in the same instrument, it is very necessary to use great care in making connections. **Always note carefully the diagram and instructions furnished with the instrument.**

Multipliers and potential transformers are often used in connection with the voltage circuit and current transformers with the current circuit of wattmeters.

Frequency Meters. For accurate measurement work, especially in laboratories, as well as in stations and sub-stations, it is desirable to know the exact frequency of a circuit at all times. This is determined by a frequency meter or indicator.

Two common types of frequency meters are the **vibrating reed** and **induction types.**

The **vibrating reed** meter has a series of metal reeds of various lengths and weights mounted over an electro-magnet, supplied with current from the source, whose frequency is to be measured. Each reed has a natural period or frequency of vibration. If the current passing through the magnet has a frequency the same as the natural vibration frequency of one of the reeds, then that reed will vibrate rapidly through a wide range. The other reeds will not be affected. Figure 19 shows an instrument of this type.

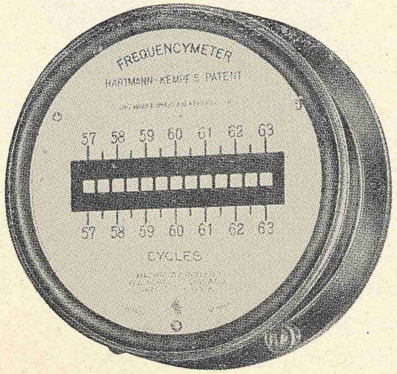

Figure 19—Vibrating Reed Frequency Meter. Roller-Smith Company

The induction-type frequency meter is similar to the induction-type voltmeter, except that the cylinder or disk is actuated by a flux proportional to the frequency instead of proportional to voltage. This result is obtained by having the torque produced by two coils, one having a current passing through a non-inductive resistance and the other through an inductive resistance. Changes of voltage affects both coils alike and produces no change in the torque, but changes in frequency changes the current through the inductive winding but not through the non-inductive coil, and thus produce a change in torque and a movement proportional to the change in frequency.

Figure 20 shows the interior of a Westinghouse switchboard frequency meter of this type.

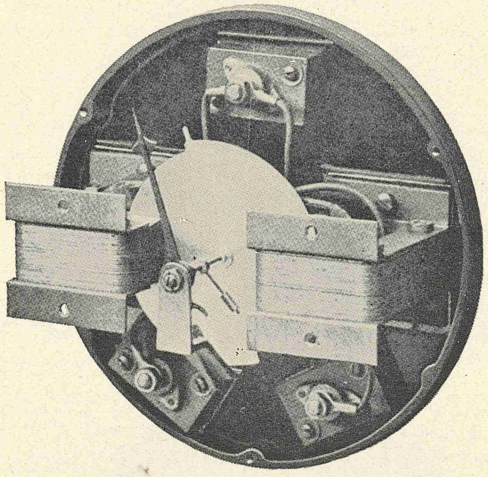

Figure 20—Induction Type Frequency Meter—Westinghouse

Power-Factor Meters. On alternating current circuits, especially at stations and sub-stations, it is very necessary to have instruments for measuring power factor. As power factor depends upon the phase difference between the current and voltage of a circuit, it means that the torque of a power-factor meter must be proportional to this difference of phase.

This instrument must, therefore, have both current and voltage coils, so arranged and connected that there is zero torque produced with no phase difference and an increasing torque, with increasing difference of phase. Figure 21 is a sketch of the coils and connections of a three-phase power factor meter, S and S being the stationary current coils and M and M the movable coils connected to the pointer.

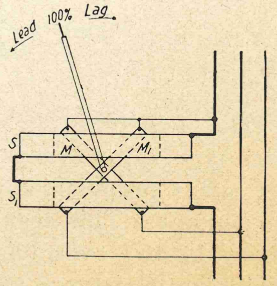

Figure 21—Diagram of Connections of a Three-Phase Power-Factor Meter. Westinghouse

Switchboard Instruments. Indicating instruments may be dvided into two general classes, portable instruments and switchboard instruments. Portable instruments are those designed primarily for accurate testing work and are intended to be easily carried around and are provided with carrying cases. Switchboard instruments are larger and are intended for switchboard mounting. They are usually less accurate, more rugged and require more power to operate than the portable instruments. Switchboard instruments are made in many different styles for various methods of mounting, such as: round type, horizontal edgewise, and vertical edgewise.

The principles of construction and operation of switchboard instruments are practically identical with the portable instruments, the principal difference being size.

Binding Posts. On all measuring instruments, the binding posts or terminals of the current coils are of bare metal, while the terminals of all pressure coils are rubber covered, to avoid shocks and short circuits. This difference in terminals is worth noting as it enables a person to distinguish, at a glance, voltmeters from ammeters, and current terminals from voltage terminals on wattmeters and similar instruments.

Instrument Scales. The division of the scale of electrical instruments differs with the type of instrument. Instruments such as the D'Arsonval type have a uniformly graduated scale; that is, one unit is the same on all parts of the scale. A scale of this kind is shown in Figure 22. Instruments of the hot-wire or electro-dynamometer type give deflections proportional to the square of the current or voltage applied and therefore have what is called a **square-root scale.** The deflection

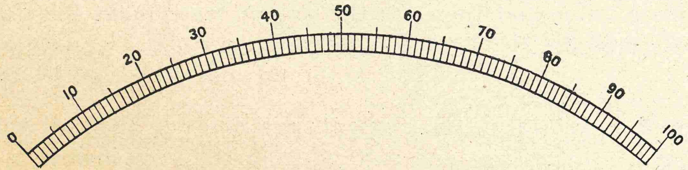

Figure 22—Scale of D'Arsonval Type Instrument

for a double value of current or voltage is not twice as great, as with the D'Arsonval instruments, but four times as great. This gives a scale such as shown in Figure 23. Low values cannot be read closely. In all instruments the most accurate readings are those near full scale deflection.

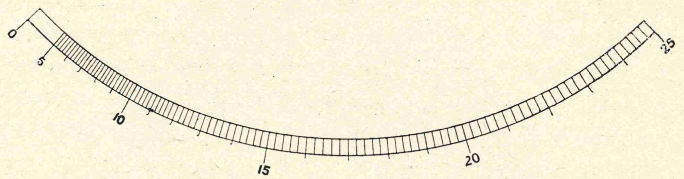

Figure 23—Scale of Hot-Wire or Dynamometer Type Instruments

Reading an Instrument. In reading an instrument the eye should be placed directly over the needle so as to avoid errors of parallax. Most instruments are provided with a small strip of mirror below the needle so that the observer can see the reflection of his eye in the mirror. The eye should be placed so that the needle passes directly across the center of the pupil of the eye as seen in the mirror. Instruments can be read directly to the closest division and usually can be easily estimated to one-tenth of a division, if close readings are required.

Whenever possible an instrument should be selected so that the reading to be taken lies within the last quarter of the scale. That is to say, if the current to be read is about 8 amperes, an instrument with a scale reading from 0 to 100 could be used, but it would be much better to use one with a scale from 0 to 10. Where the value to be read is not known approximately, it is well to use a very high reading instrument to determine the approximate value and then use the proper instrument to take an accurate reading.

Range of Readings. Indicating instruments are made to read all values of current and voltage from the very lowest, a few thousandths of an ampere or volt, by instruments called milliammeters and millivoltmeters, to ammeters with shunts or current transformers reading thousands of amperes and voltmeters with multipliers or pressure transformers reading thousands of volts.

Jewel Bearings. In order to insure greater accuracy and lasting qualities, all high grade instruments are equipped with jewel bearings, usually sapphires, for the pointer shaft. This construction practically eliminates friction and enables the instrument to remain accurate over a long period of time. Great care must be taken in handling instruments to see that they are handled carefully because a severe jolt or jar is likely to injure the delicate pivots and jewels.

Dampers. In order to make the movement of the instrument needle steady and to bring the needle to rest quickly, indicating instruments are provided with some form of damper, such as an aluminum vane attached to the needle and moving in a metal box, or an aluminum disc moving between the poles of a permanent magnet. These are of great help, especially when taking measurements of fluctuating values of current or voltage.

Calibration of Instruments. When instruments leave the factory they are in good condition and accurately calibrated. Upon receipt they should be carefully examined and tested to be sure that they have not been injured in transit. Where there are facilities for testing, the instruments should be checked against a standard instrument at frequent intervals. Where there are no such facilities, the instrument should be returned periodically to the maker for general overhauling and calibration.

Effects of Stray Fields. Magnetic types of instruments are more or less affected by stray magnetic fields and should therefore not be used close to dynamo fields or near bus-bars carrying large currents. Many makes of instruments are provided with magnetic shields; that is, the mechanism of the instrument is almost entirely enclosed in an iron case so as to prevent stray magnetic fields from passing through the instrument.

Instrument Transformers. Shunts for ammeters and multipliers for voltmeters are little used in alternating-current instrument work. One reason for this is that so much of the work is on high voltage circuits that it would be very dangerous to use instruments connected directly to the high voltage circuits.

Current Transformers. **Current transformers** are used to transform current to low values and **Potential transformers** or **Pressure transformers** to transform the pressure to low values for the instruments.

A current transformer is a simple, small transformer, built practically the same as described in Lesson 7, except that the windings are of comparatively few turns and of larger wire. The actual energy transformation from primary to secondary is small, only a few watts, therefore the current transformers are relatively small. The manner of connecting a current transformer is shown in Figure 24. The primary of the current transformer is connected in series with the lines, the same as an ammeter, because it is current we wish to transform, while the secondary is short circuited through an ammeter or other meter through which the secondary current is to pass. These transformers are designed to give a very accurate ratio between primary and secondary currents. The ratios of primary to secondary currents may be almost anything as 1:1 or 4:1, 10:1, 20:1, etc.; it is merely a matter of relative number of turns. A given number of ampere turns on the primary will produce the same

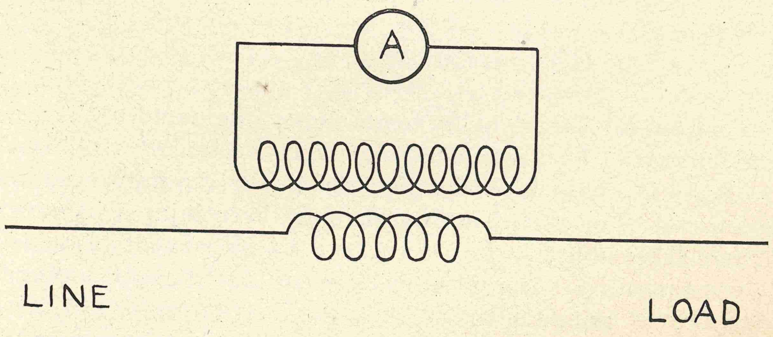

Figure 24—Diagram of Connection for a Current Transformer

number of ampere turns on the secondary. It has become quite standard practice to have the full-load secondary current, on current transformers, 5 amperes. This is very desirable as all instruments can be made for 5 amperes and all secondary or instrument wiring is in small wire.

It is well to keep in mind that a current transformer may answer one or two purposes; namely, **to insulate the meters from the high voltage circuits,** as a safety measure, and **to reduce the current flowing through the instrument circuits.**

There is one precaution that must **always** be observed in using current transformers: **Always keep the secondary (instrument side) short circuited either through the instrument** or through a **short circuit across the terminals of the secondary.**

If this precaution is not taken and current is passed through the primary, with the secondary open, a very high voltage is induced in the secondary, high enough to endanger life and also endanger the insulation of the transformer.

One type of current transformer is shown in Fig. 25.

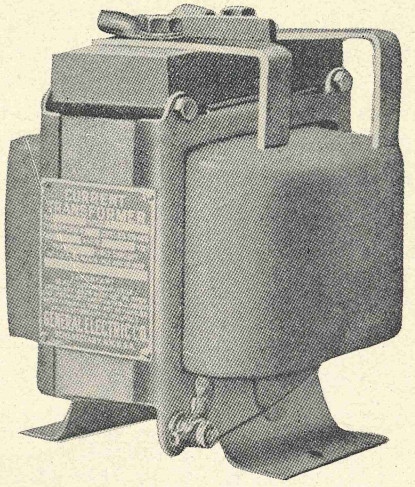

Figure 25—Switchboard Type of Current Transformer

Current transformers are often made for portable use so that any number of turns desired can be wound on the primary. A transformer of this kind is shown in Figure 26. The primary conductor is simply wound through the opening. For example, if the secondary is wound with 80 turns for 5 amperes then a single turn of wire, through the opening, carrying 400 amperes would give an 80:1 ratio. If it is desired to measure a current as high as 200 amperes, use two turns on the primary, or of 100 amperes, use four turns. As long as the product is 400 ampere turns, the secondary will deliver 5 amperes. This is an exceedingly useful transformer as with it and a 5-ampere ammeter, any current from 0 to 400 amperes can be accurately measured.

Another type of portable current transformer of variable ratio is so made that the ratio can be changed by changing plugs on a plug type terminal board.

For measuring alternating current in heavy cables a current transformer is made with a split, hinged iron core, so that the transformer can be slipped over the cable and the current read without interruption of service or the necessity of opening up the circuit to make connections. This type is shown in Figure 27.

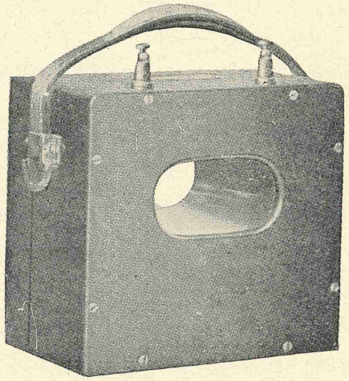

Figure 26—Portable Current Transformer, Variable Ratio—Westinghouse

Current transformers are used in a. c. station and sub-station to supply ammeters, wattmeters, watt-hour meters, power-factor meters, compensators and often trip coils on switches.

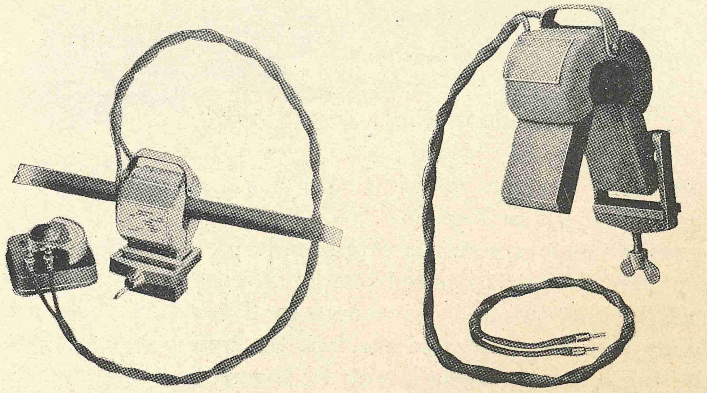

Figure 27—Current Transformer for Cables—General Electric Co.

Potential Transformers. Potential transformers are simple small transformers of very accurate ratio of primary to secondary voltage. They are small because they are of low capacity, seldom over 500 watts, all that is necessary to supply voltmeters and pressure coils of other instruments and apparatus. The primary of the potential transformer is wound for the full voltage of the circuit, while the secondary is wound to deliver usually from 100 to 125 volts to instruments. Connections for a potential transformer are shown in Figure 28.

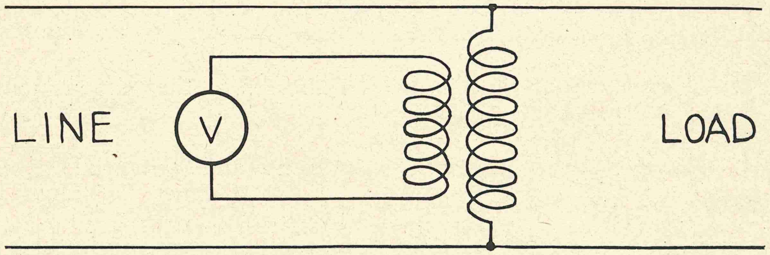

Figure 28—Connections for a Potential Transformer and Voltmeter

Potential transformers are made for both switchboard and portable work. A switchboard type of potential transformer is shown in Figure 29.

Potential transformers are used in a. c. stations and sub-stations to supply voltmeters, wattmeters, watt-hour meters, power-factor meters, synchroscopes, trip coils of switches, alarm bells, pilot lamps, switchboard lamps.

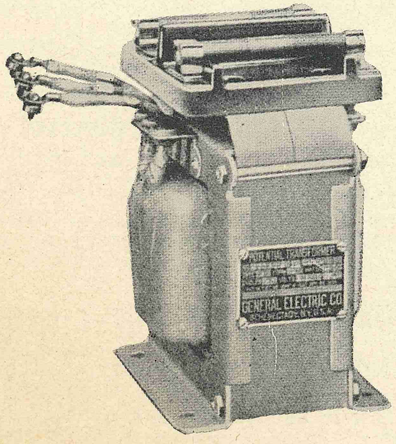

Figure 29—Potential Transformer, Switchboard Type

Conclusion. Students wishing to go more deeply into the subject of meters will find much additional information in the reference books listed on page 28.

DEMONSTRATION FOR LESSON VIII.

1. If possible secure a few early types of switchboard instruments, which can be taken apart for study.

2. Have several types of ammeters, voltmeters and wattmeters, for inspection.

3. Connect up ammeters and voltmeters so that the students can see the actual connections.

4. Have shunts, multipliers, current and potential transformers for inspection.

REFERENCE BOOKS

N. E. L. A. Electrical Meterman's Hand-book.

American Meter Practice, by Lyman C. Reed. McGraw-Hill Pub. Co., New York.

Electrical Meters, by Cyril M. Jansky. McGraw-Hill Pub. Co., New York.

Electricity Meters, by Henry G. Solomon. J. B. Lippincott Co., Philadelphia.

QUESTIONS

Note: These questions are to be answered after the lesson has been studied carefully, and without further reference to the lesson.

1. Compare ammeters and voltmeters as to principle of operation.

2. Describe briefly the hot-wire type of instrument.

3. Describe briefly the D'Arsonval type of instrument.

4. Explain fully the use of a shunt.

5. Explain fully the use of a multiplier.

6. Upon what principle does the indicating-wattmeter operate?

7. What purposes are served by current transformers?

8. What purposes are served by potential transformers?

INDEX

Page
Alternating Current Instruments 14
Ammeter Shunts 9
Ammeters and Voltmeters 4
Binding Posts 21
Calibration of Instrument 23
Dampers 23
D'Arsonval Type 7
Dynamometer Type Instruments 13
Electrostatic Voltmeter 15
Frequency Meter 19
Hot Wire Instruments 8
Jewel Bearings 23
Magnetic Vane Type 7
Measurement of Electrical Quantities 3
Multipliers 12
Power-Factor Meters 20
Plunger Type Instruments 5
Quantities to be Measured 3
Range of Readings 22
Reading an Instrument 22
Scales 21
Shunts 9
Stray Fields, Effects of 23
Switchboard Instruments 21
Transformers, Current 24
Transformers, Instrument 24
Transformers, Potential 26
Wattmeter 16

NOTICE.

Special sheets for answers to test questions have been sent to you. These answers should be sent to the Chairman within 30 days. They will be corrected, graded and returned to you direct or through your class leader.

Certificates will be granted to those obtaining an average grade of 70 per cent or over.

These lessons will not be forwarded, therefore any change of address must be reported immediately to the Chairman by separate letter.

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LESSON IX : : : MEASUREMENT OF POWER

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INTRODUCTION

A study of the subject of power measurement will give the reader a better knowledge of fundamental electrical principals, as well as aid him in making actual power measurements.

Answer the Questions on Each Lesson.

If you are not answering the questions on each lesson you are not getting as much benefit from the course as you are entitled to. **Remember, that what you get out of this course depends upon what you put into it.**

Also, the examiner of your papers will make valuable suggestions to you and will correct wrong impressions, thus making your knowledge more exact and valuable.

The certificate granted, to those who satisfactorily complete the course, **has real tangible value.** It is the best evidence that you are an ambitious, earnest worker, that what you need you go after, and what you go after you get. **Get the certificate.**

Answer the questions on those back lessons now. There is still time, and the review of the lessons will be well worth while.

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LESSON IX—MEASUREMENT OF POWER.

Definition of Power. **Power is the rate of doing work.** In a direct-current circuit the rate of doing work depends upon the number of amperes flowing in the circuit and the voltage or pressure of the circuit.

In an alternating-current circuit the rate of doing work, or power, depends upon the current, voltage and power-factor of the circuit.

In both direct-current and alternating-current circuits, the power in the circuit is expressed in **watts,** or if the amount of power is large, in **kilowatts.**

The electrical unit of power is the watt, and power in electric circuits is expressed in watts or kilowatts, as, for example, a 100 watt lamp or a 1,000 kilowatt generator.

The mechanical unit of power is the horse power, and mechanical power devices, such as engines, turbines or water-wheels, are rated in horse power.

As both the watt and horse power are units of power, there must be a fixed relation between these units. This is as stated below:

1 horse power=746 watts.

To convert horse power into watts multiply the number of horse power by 746.

Horse power × 746 = watts.

As, for example, the equivalent of 25 horse power, in watts, is found thus:

25 × 746 = 18,650 watts = 18.65 kilowatts.

Watts are converted into horse power by dividing the number of watts by 746.

$$\text{Watts} \div 746 = \text{horse power.}$$

For example, the equivalent of 1,000 watts in horse power is found as follows:

$$1{,}000 \div 746 = 1.34 \text{ horse power.}$$

That is, 1,000 watts, or 1 kilowatt, is equal to 1.34 horse power.

An electric motor is rated in horse power because its output is mechanical. The input of the motor is measured in electrical units. In determining the efficiency of a motor, that is, the ratio of output to input, it is necessary to have both output and input expressed in the same units, either horse power or watts, thus:

$$\text{Efficiency of the motor} = \frac{\text{Output}}{\text{Input}}$$

$$\text{`` \quad `` \quad `` \quad ``} = \frac{\text{Horse power output} \times 746}{\text{Watts input}}$$

giving both output and input watts.

Or,

$$\text{Efficiency} = \frac{\text{Output}}{\text{Input}}$$

$$= \frac{\text{Horse power output}}{\text{Watts input} \div 746}$$

giving both output and input in horse power.

Power Rating. The rating of **direct-current generators** is always in terms of power output under full-load conditions and is given in kilowatts.

$$\text{Kilowatt Rating} = \frac{\text{Full-load amperes} \times \text{Full load volts}}{1{,}000}$$

The same statement would apply to **alternating-current generators** and **transformers** if unity power factor is considered. It will be remembered, however, that with alternating current the actual power output varies with the power factor, although the current and voltage remain the same. Therefore, a power rating on a.-c. generators and transformers is of no value unless the power factor is stated.

$$\text{Kilowatts Output} = \frac{\text{Amperes} \times \text{Volts} \times \text{Power factor}}{1{,}000}$$

An a.-c. generator or transformer rated at 1,000 kw. at 100 per cent power factor would be rated at 900 kw. at 90 per cent power factor and 750 kw. at 75 per cent power factor.

For this reason a.-c. generators and transformers are now seldom rated in actual power, that is, kilowatt output, but in apparent power output or in kilovolt-amperes.

$$\begin{array}{c}\text{Kilovolt-Ampere}\\ \text{Rating}\end{array} = \frac{\text{Full-load current} \times \text{Full-load volts}}{1{,}000}$$

Motors, both d-c. and a-c., are rated in horse power output, under full-load conditions.

Power in a Direct-Current Circuit. As was explained in Lesson 2, the power expended in a direct-current circuit equals the produce of voltage multiplied by current, that is,

$$\text{Watts} = \text{Volts} \times \text{Amperes}$$

$$\text{Watts} = E \times I \tag{1}$$

This is true for the whole circuit or any part of the circuit. If only a part of the circuit is considered, then of course the watts expended in that part of the circuit equal the voltage of that part of the circuit multiplied by the current in that part of the circuit. If the circuit is made up entirely of resistance, that is, contains no batteries or motors or other device having a counter-pressure, then the equation, for watts expended in the circuit, may be expressed in any of the following forms:

$$\begin{aligned} & \text{Watts} = E \times I \qquad \text{as above,}\\ \text{or since} \quad & E = R\,I \\ \text{then} \quad & \text{Watts} = R\,I^2 \end{aligned} \tag{2}$$

or substituting for I in the first equation, its value

$$I = \frac{E}{R}$$

this equation becomes

$$\text{Watts} = \frac{E^2}{R} \tag{3}$$

Consider the simple resistance circuit of Figure 1. The voltage is 120, the current 5 amperes and the total resistance 24 ohms. The power expended in this circuit can be found by

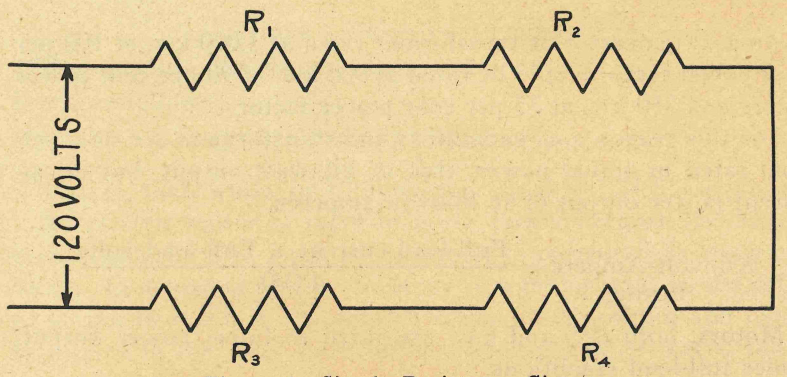

Figure 1—Simple Resistance Circuit

Using equation 1:

Watts $= E \times I$
“ $= 120 \times 5$
“ $= 600$

Using equation 2:

Watts $= R\ I^2$
“ $= 24 \times 5 \times 5$
“ $= 600$

Using equation 3:

$$\text{Watts} = \frac{E^2}{R}$$

$$\text{“} = \frac{120 \times 120}{24} = \frac{14{,}400}{24}$$

“ $= 600$

Considering any part of the circuit, such as the second resistance, of 3 ohms: The current in this part of the circuit is 5 amperes, the resistance 3 ohms and the voltage therefore $(E = RI) = 3 \times 5 = 15$ volts. The power used in this part of the circuit can be found by using any one of the three equations given previously. Using equation 1,

Watts $= E \times I$
“ $= 15 \times 5$
“ $= 75$

and similarly with equations 2 and 3.

If the circuit is a motor or a battery circuit, then the easiest method of determining the power delivered to the motor or battery is to measure the total current and the voltage across the motor or battery, using connections as shown in Figure 2. The power is then found by equation 1.

Watts $= E \times I$

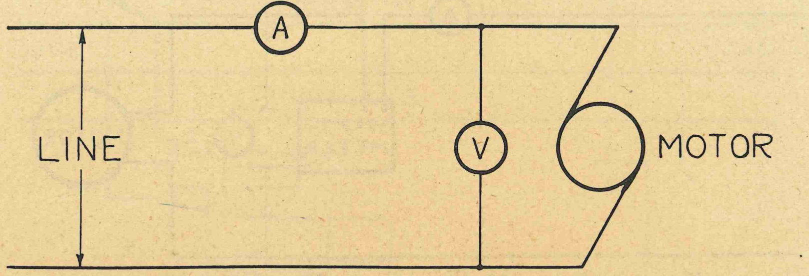

Figure 2—Measurement of Power with Ammeter and Voltmeter

Power in a Simple Alternating-Current Circuit.

If an alternating-current circuit is made up entirely of non-inductive resistance, then the power used in the circuit is found in exactly the same way as for a direct-current circuit.

Watts $= I^2\ R$
“ $= E \times I$

However, as most alternating-current circuits contain more or less inductance, causing the current to be out of phase with the voltage, the question of power factor must be considered. Therefore the general expression for power in any a-c. circuit is:

Watts = Volts × Amperes × Power factor

The usual method of determining the power in a single-phase circuit is to use an indicating wattmeter as described in Lesson 8. The reading of the wattmeter is always the true power in the circuit, regardless of power factor.

If it is desired to determine the value of the power factor, ammeter and voltmeter readings can be taken and the power factor determined from the relation expressed in the equation for power factor, i. e.,

$$\text{Power factor} = \frac{\text{True Watts}}{\text{Apparent Watts}}$$

$$\text{`` \quad ``} = \frac{\text{Wattmeter reading}}{\text{Volts} \times \text{amperes}}$$

For example, consider Figure 3, which illustrates an alternating-current circuit in which the current is not in phase with the voltage. The ammeter reading is 10 amperes, the voltmeter 115 and the wattmeter 1,000 watts.

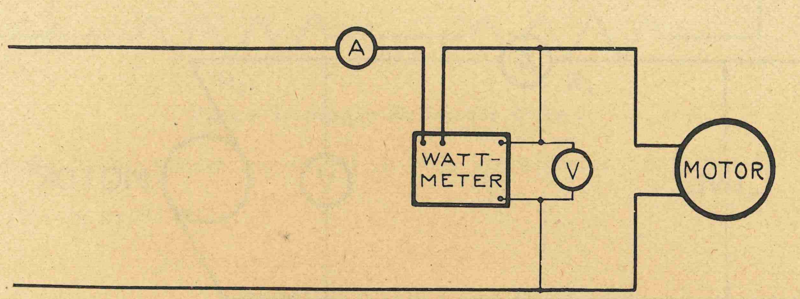

Figure 3—Power Measurement in Simple A. C. Circuit

$$\text{Power factor} = \frac{1000}{115 \times 10} = \frac{1000}{1150}$$

$$\text{`` \quad ``} = 0.87 \text{ or } 87. \text{ per cent.}$$

Power in a Two-Phase Circuit. If a two-phase circuit is balanced, that is, has the same load on both phases, as would be the case if the load was all two-phase motors, then the reading of a wattmeter placed in either phase would be one-half of the total power. In all cases, whether the load is balanced or unbalanced, the total power is the sum of the wattmeter readings of the two phases. One wattmeter can be used to read the power, in both phases, if an arrangement for switching the wattmeter from one phase to the other, as illustrated in Figure 4, is provided. Great care must be taken, of course, that the wattmeter is disconnected from one phase before it is connected to the other, or a serious short-circuit will occur. As shown in Figure 4 the wattmeter is connected so as to read power in phase A. To transfer the meter to phase B close the switch marked 1, thus short-circuiting the ammeter and the current coil of the wattmeter, then open switches 2 and 3. The wattmeter is then disconnected from both phases. Now close switch 2 on the B side and open switch 4, thus connecting the ammeter and current coil of the wattmeter, in phase B. Closing switch 3 on the B side connects the voltmeter and the pressure coil of the wattmeter to phase B. The sum of the wattmeter readings on the A and B phases gives the total power.

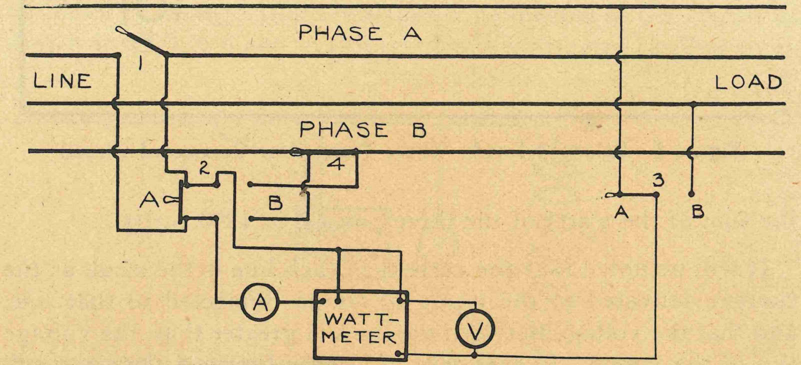

Figure 4—Connections for Measuring Power in a Two-Phase Circuit

The power factor can be determined for each phase separately and the average of the two will be the average power factor of the load.

If two wattmeters are available, then matters are simplified by using a separate wattmeter for each phase.

Voltage Current and Power in A Three-Phase Star Connected Circuit. A three-phase star connected circuit having a balanced load of lamps is represented in Figure 5. For simplicity, assume that each lamp is a 200 watt, 100 volt lamp, then each lamp takes 2 amperes, and since each line carries the current for two lamps, then each line carries 4 amperes. Each phase has two, 200 watt lamps, therefore the power delivered to each phase is 400 watts and the total power delivered to the three-phase circuit is three times the power delivered to any phase, since the load is balanced, or the sum of the watts of the three phases, or 1200 watts.

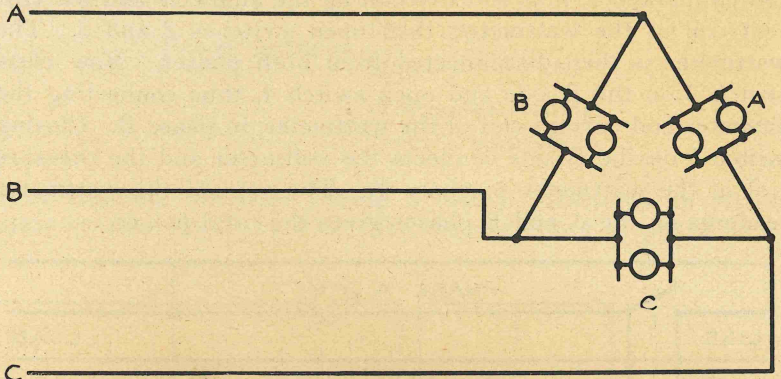

Figure 5—Balanced Load. Three-Phase Star Connected Circuit

It will be noted that the current in each line is the same as the current delivered to the group of lamps connected to that line, and that the voltage between the lines is greater than the voltage across the lamps. In this case 173. volts between the lines will give 100. volts across the lamps.

In any star connected circuit, the current in each line is the same as the current in the phase, that is

$$I_L = I_P$$

and the voltage between lines is 1.73 times the voltage between line and neutral:

$$E_L = 1.73 \times E_P$$

In terms of the current in the line and voltage between lines the power delivered to each phase, or groups of lamps, is

$$\text{Watts per phase} = \frac{E_L}{1.73} \times I_L \times \text{Power Factor.}$$

$$\text{`` \quad `` \quad ``} = \frac{173}{1.73} \times 4 \times 1$$

$$\text{`` \quad `` \quad ``} = 400$$

The total power delivered to the three-phase system is three times the watts per phase or

$$\text{Total watts} = (3\frac{E_L}{1.73} \times I_L \times \text{Power Factor})$$

$$\text{`` \quad ``} = 1.73\ E_L \times I_L \times \text{Power Factor.}$$

or in the case considered:

$$\text{Total watts} = 1.73 \times 173 \times 4 \times 1$$
$$\text{`` \quad ``} = 1200 \text{ watts}$$

The power in any balanced star-connected circuit can be determined by using a single wattmeter connected in the circuit as shown in Figure 6 and multiplying the wattmeter reading by 3.

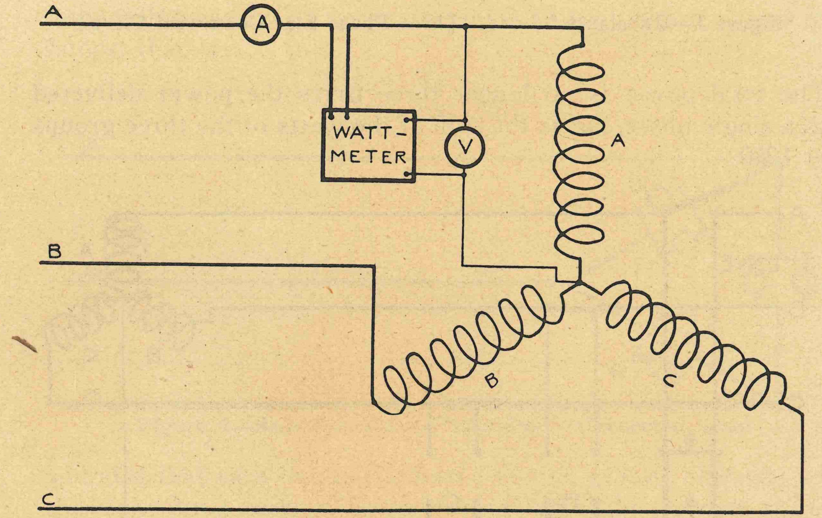

Figure 6—Connections for Power Measurement, Balanced Load, Star Connected Three-Phase Circuit

Now consider the same circuit but with the lamps connected so as to make an unbalanced load as represented in Figure 7. Phase A has three lamps, each taking two amperes, therefore line A carries 6 amperes. Phase B has two lamps, therefore line B carries 4 amperes while Phase C has one lamp and line C carries 2 amperes. The power delivered to each phase is as follows: A, 600 watts; B, 400 watts; C, 200 watts.

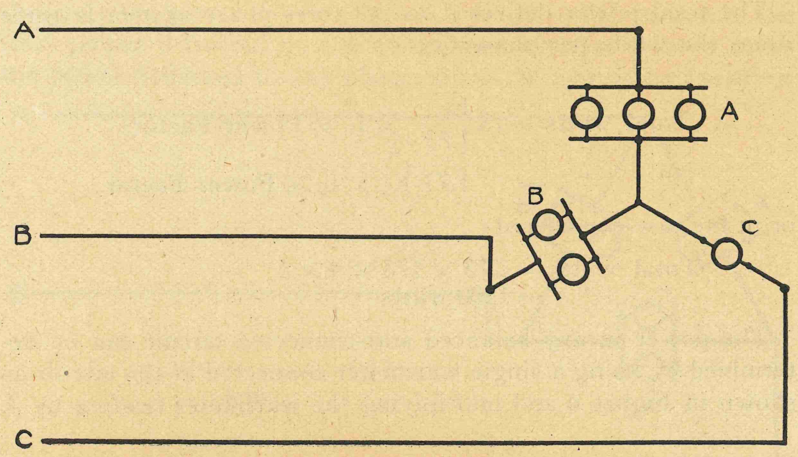

Figure 7—Unbalanced Load. Three-Phase Star Connected Circuit

The total power is no longer three times the power delivered to a single phase, but is the sum of the watts of the three groups or 1200.

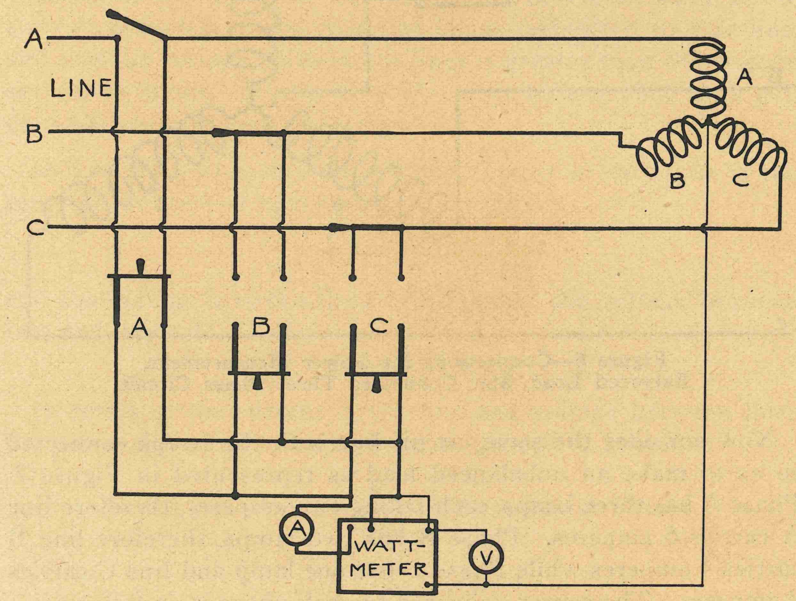

Figure 8—Connections for Power Measurement, Balanced or Unbalanced Loads

One method of measuring the power in this or any unbalanced star-connected circuit is to use three wattmeters, one for each group of lamps and each connected the same as the one shown in Figure 6. The total power is then the sum of the three wattmeter readings.

Another method is to use one wattmeter, with a switching arrangement, as shown in Figure 8, by means of which the wattmeter can be transferred from one phase to another. Here, too, the sum of the three readings will give the total power.

Three-phase Delta-Connected Circuit. Consider now a balanced three-phase delta connected circuit, as represented in Figure 9 and again assume two 200 watt, 100 volt lamps per phase. It will be seen that the voltage between the lines is the same as the voltage across the lamps, that is:

$$E_L = E_P$$
$$E_L = 100 \text{ volts}$$

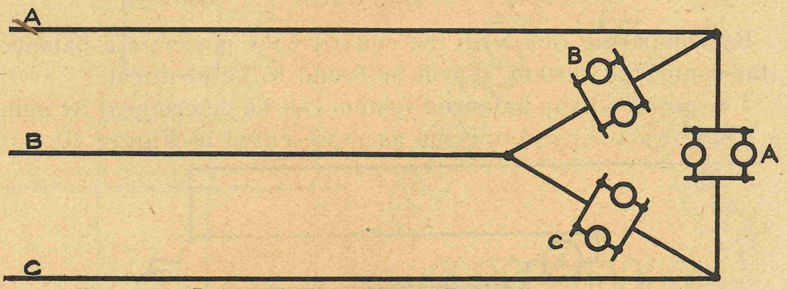

Figure 9—Balanced Three-Phase Delta Connected Load

and also that each line is connected to two groups of lamps and therefore must carry a larger current than the current of one group. In a balanced delta circuit the line current is 1.73 times the phase current:

$$I_L = 1.73 \times I_P$$
$$I_L = 1.73 \times 4$$
$$I_L = 6.92 \text{ amperes}$$

The power delivered to each group of lamps is the same as in the star-connected circuit, 400 watts, and the total power is the same, that is, three times the power of a single phase or the sum of the three phases, that is, 1200 watts.

In terms of the current in the line and the voltage between lines the expression for the power for each phase is:

$$\text{Watts per phase} = E_L \times \frac{I_L}{1.73} \times \text{Power Factor.}$$

In this particular case:

$$\text{Watts per phase} = 100 \times \frac{6.92}{1.73} \times 1.$$

$$\text{“} \quad \text{“} \quad \text{“} = 400$$

The total power delivered to the three-phase balanced delta-connected system is three times the power per phase or

$$\text{Total watts} = 3 \left(E_L \times \frac{I_L}{1.73} \times \text{Power Factor.}\right)$$

$$\text{“} \quad \text{“} = 1.73\, E_L \times I_L \times \text{Power Factor.}$$

or in the case considered

$$= 1.73 \times 100 \times 6.92 \times 1.$$
$$= 1200 \text{ watts.}$$

By comparing this with the equation for power in a balanced star-connected system, it will be found to be identical.

The power in any balanced system can be determined by using a single wattmeter connected as represented in Figure 10, with

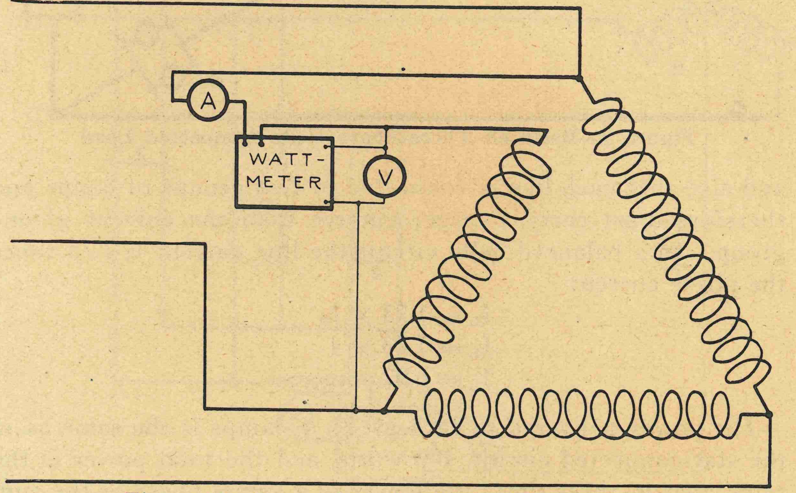

Figure 10—Connections for Power Measurement Balanced, Delta Connected Load

its current coil in the phase and its voltage coil across the line, and multiplying the reading by three. If the load is unbalanced the three wattmeters could be similarly connected and the sum of their readings would give the total power.

As it is not usually possible to connect the current coil into the phase, some other method must be used.

For a delta-connected circuit, or for a star-connected circuit where the neutral is not available, an artificial neutral may be formed by using three equal resistances or inductances, star-connected. This artificial neutral can be used in power measurements in the same manner as the neutral point of a star-connected system.

If the load is balanced, one wattmeter with the current coil connected in any line and the voltage coil connected from that line to the artificial neutral, will read one-third of the total power. This is as shown in Figure 11.

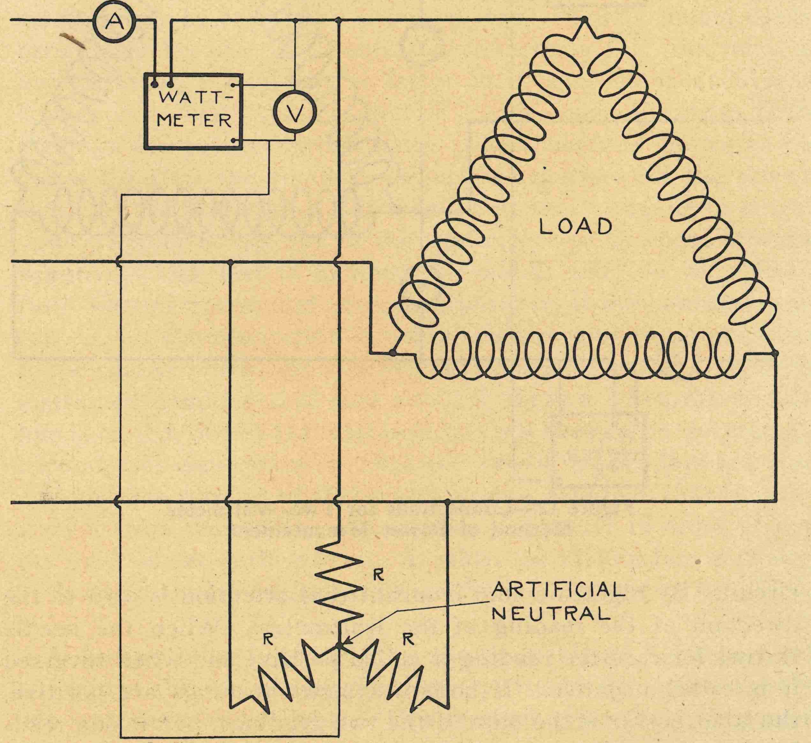

Figure 11—Connections for Measurement of Power, using Artificial Neutral

If the load is unbalanced, three wattmeters similarly connected, one in each line, or one wattmeter arranged to be switched from one line to any other can be used to determine the total power.

Two-Wattmeter Method. The simplest method to use for the measurement of three-phase power is the **two-watt meter method.** If two wattmeters are connected as shown in Figure 12, the algebraic sum of the two readings will give the total power in a three-phase system, no matter what the condition of balance, or whether in a star or delta circuit. By algebraic sum is meant that attention is paid to the direction of the reading of the wattmeter. When the needle throws forward the reading is called positive and when reversed it is called negative. If both wattmeter readings are positive, the total power is the sum of the two readings, but if one reading is negative then the total power is the difference of the two

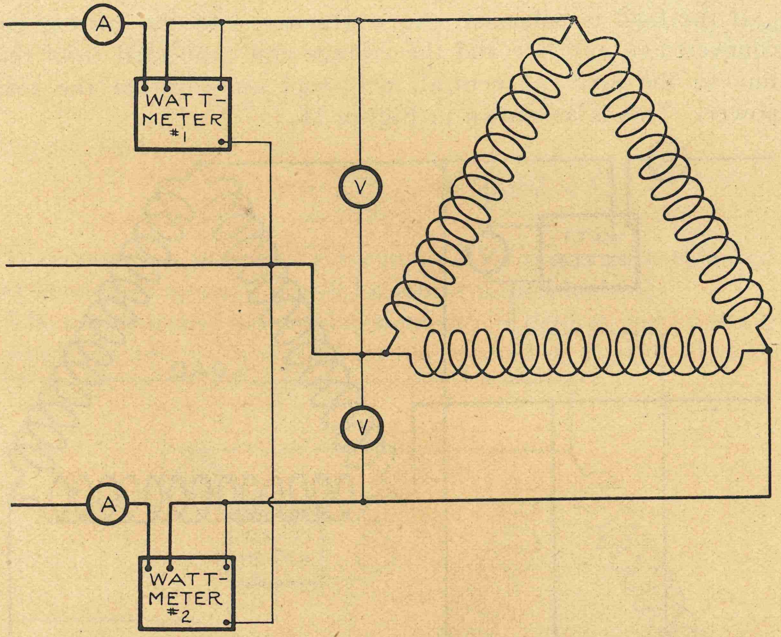

Figure 12—Connections for Two-Wattmeter Method of Power Measurement

readings. Each wattmeter reads one-half of the total power if the power factor is unity, and both readings are positive if the power factor is greater than 0.5, while if the power factor is less than 0.5, i. e., if the lead or lag is greater than sixty degrees, one wattmeter reading is positive and the other negative. For example, if two wattmeters are used to measure the power input, into an induction motor, they will be found to read positively and about the same when the motor is fully loaded, because the power factor is high at full load, but as the load decreases one wattmeter reading becomes higher than the other, because the power factor is becoming lower, while at no load one wattmeter is very apt to read slightly negative because the power factor of the induction motor at no load is very apt to be below 0.5.

In using the two-wattmeter method care must be taken to see that the two wattmeters are similarly connected, otherwise a reading may be considered negative, when the instrument reads backwards because of a reversed connection. If the load is known to be a high power factor load, such as incandescent lamps, or a well loaded induction motor, then of course both readings are positive, while if the power factor is known to be below 0.5 then the smaller reading is negative. If the power factor of the load is doubtful then a test may be made to determine whether or not one of the readings is to be considered as negative. One test is to open the middle line, on light load. Both wattmeters should then read positive, if the connection is correct. If the connection is not correct, reverse the connection to the current coil of the instrument reading backward, then both instrument readings will read forward. If now when the middle line is closed, one of the wattmeters reads backwards, reverse its current coil connection, so that the needle moves forward and consider the reading of that wattmeter as negative, that is, subtract it from the reading of the other wattmeter in order to get the total power in the circuit. If when the middle line is closed both wattmeters read forward then the readings are to be added.

A dynamometer board such as shown in Figure 8 can be used to change the instrument from one phase to the other if only one wattmeter is available. This method gives the true power for both star and delta connected loads.

Polyphase Wattmeter. The principle of the two-wattmeter method of power measurement is used in what is known as a polyphase wattmeter.

This instrument has two complete wattmeter elements working on a single shaft and pointer. The torque moving the pointer is thus always the algebraic sum of the torques developed by the two elements and the reading is the same as would be obtained by taking the algebraic sum of two entirely separate wattmeters.

Example of Power Measurement. Consider for example the measurement of power input of a 5 horse power, single-phase 220 volt motor. The diagram of connections would be as given in Figure 13. The following instruments would be needed:

1—A-c. ammeter 0-25.
1—A-c. voltmeter 0-250 volts.
1—Wattmeter 25 amp., 300 volt, 7500 watts.

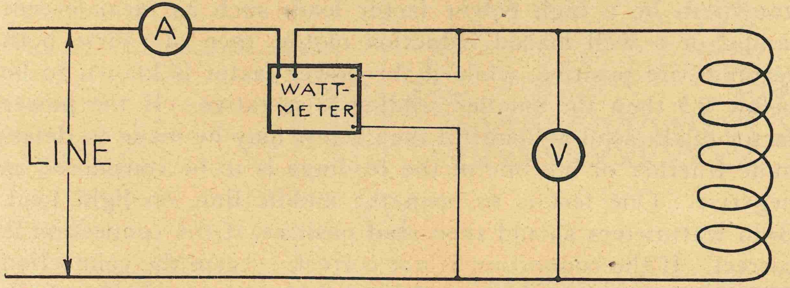

Figure 13—Connections for Power Measurement-Single-Phase Motor

When taking readings all instruments should be read at as nearly the same time as possible.

These readings will give, as a rule, all information desired regarding the input, namely, voltage, current, power and power factor.

A Useful Combination of Instruments. Where it is desired to reduce the investment in measuring instruments to a minimum, the following makes almost an ideal combination of apparatus for measuring power over a wide range of conditions:

1—Portable, variable ratio current transformer as described in Lesson 8, page 25.
1—A-c. ammeter 0-5 ampere.
1—A-c. voltmeter 0-150-300 volts (double scale).
1—Wattmeter, 5 amperes, 150-300 volts.
1—Dynamometer board as in Figure 8.

Connected as shown in Figure 14 this equipment can be used for measuring single-phase power from currents of 5 amperes to the limit of the current transformer, 400 amperes in the one described in Lesson 8, with a voltage range from 100 to 300 volts and a power range from 0 to 120 kilowatts, if the limit of the current transformer is 400 amperes. With the aid of the dynamometer board the same connections can be used for measuring two or three-phase circuits with the same current and voltage range.

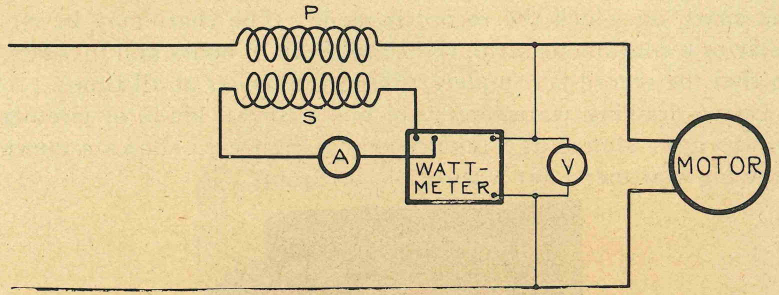

Figure 14—Connections for Power Measurement—Single-Phase Motor, using Current Transformer

Taking Readings. Whenever a set of readings of electrical instruments is taken great care should be taken to write down on the sheet of readings full information concerning all instruments used such as,

Make of instrument—
Kind—
Range of scale—
Serial number—

then in case any question arises as to the accuracy of the readings, the instruments can be checked or the test repeated with the same instruments. It is also well to make a diagram of the exact connections used.

All readings should be tabulated in systematic form and complete information should be on the sheet so that anyone at any time can understand exactly what was done.

Curve Drawing Wattmeter. It is often desirable to have a continuous record of the power consumption of a certain load. This can be secured by the use of a curve drawing wattmeter. This instrument consists of a wattmeter element, i. e., current and voltage coils, which actuate a recording pen instead of a pointer and a clock mechanism driving the chart, on which the record is made. The chart may be circular or a continuous strip, calibrated both in hours and in watts, so that the record is complete, giving the power at all times.

Curve drawing wattmeters are made for all kinds of circuits and to meet almost any requirement. Figure 15 shows a curve drawing wattmeter for a three-phase circuit.

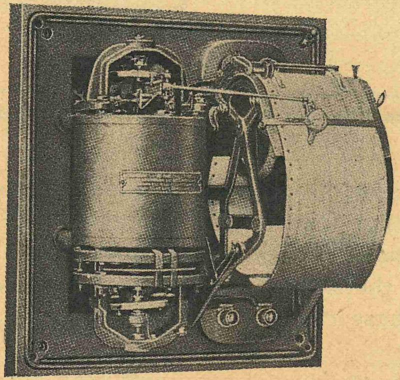

Figure 15—Three-Phase Curve Drawing Wattmeter—General Electric Co.

Maximum Demand Meters. Central Station companies have found that it is very desirable to make rates according to the customer's maximum demand for power because the amount of investment that the customer requires the company to make in order to take care of his load, and therefore the cost of service, depends largely upon his maximum demand.

A maximum demand meter is simply a meter that registers the maximum number of watts or kilowatts taken through the meter during the time between readings.

There are many such instruments on the market and in use, but for our purpose a brief description of a few of the most commonly used demand meters will be all that is necessary.

Wright Maximum Demand Meter. One of the oldest and most common of the demand meters is the Wright, shown in Figures 16 and 17. This consists of a U shaped glass tube with an air bulb at each end of U and a branch tube from the right hand bulb. The U portion of the tube is filled with colored sulphuric acid. The left hand bulb has a strip of resistance metal wrapped about it so that as the current of the circuit passes through it, it heats the air in the bulb, causing the air to expand and force some of the liquid

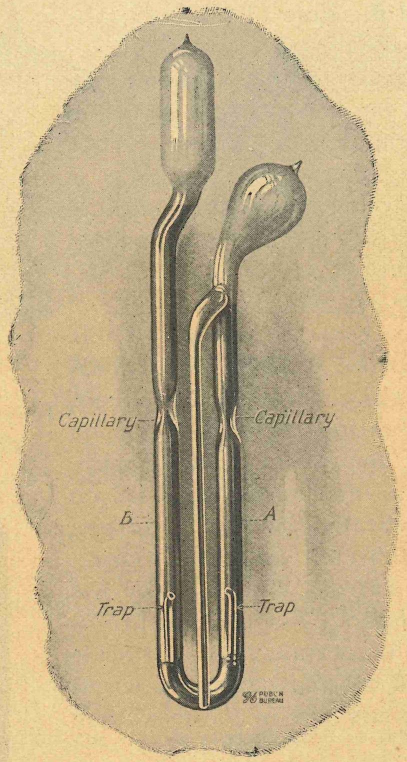

Figure 16—Tube of Wright Maximum Demand Meter

over into the branch tube. The amount of liquid forced over into the branch tube depends upon the amount of current, and the length of time it flows. That is to say, the amount of heat produced is

$$\text{Heat} = I^2 R T$$

that is, the quantity of heat is proportional to the square of the current (I^2), the resistance (R) and the time (T).

A graduated scale is placed behind the branch tube and the height of the liquid in the branch determines the reading. After the reading has been noted the tube is tipped up so that the liquid runs back to the bulb and then when the tube is lowered the liquid runs into the U tube.

It will be noted that the reading of this instrument cannot be exactly proportional to the watts passing through the circuit, inasmuch as the heating effect depends upon current and not the watts of the circuit. However, as these instruments are used on circuits of practically constant voltage, the scale is calibrated in watts, corresponding to the current multiplied by the voltage of the circuit. For convenience in making out bills on certain rates, the scale is also calibrated in kilowatt-hours corresponding to 30 hours' use of the maximum demand.

It is not desired to have instruments of this kind show the maximum power demand of short intervals such as would occur in starting motors or accidental over-loads. This instrument is slow acting and requires from 30 to 45 minutes to give the full indication.

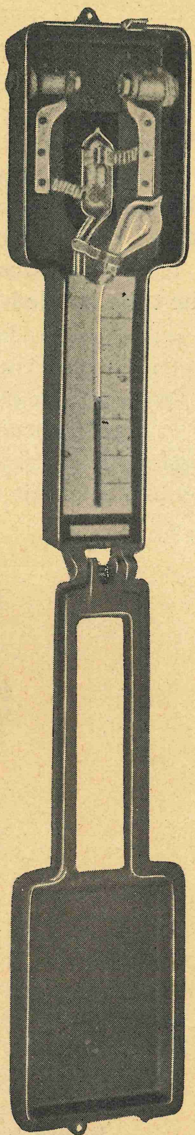

Figure 17 — Wright Maximum Demand Meter Complete, Cover Open

Type H Demand Meter. A more recent development, a more simple and less expensive maximum demand meter is the type, H of the General Electric Co., shown in Figure 18.

The mechanism of this meter consists of two springs of thermostatic metal so arranged that the current of the circuit passing through a small heating coil heats one of the springs and causes the needle to move across the scale. The needle or pointer is so driven that it remains at the highest point of travel until reset.

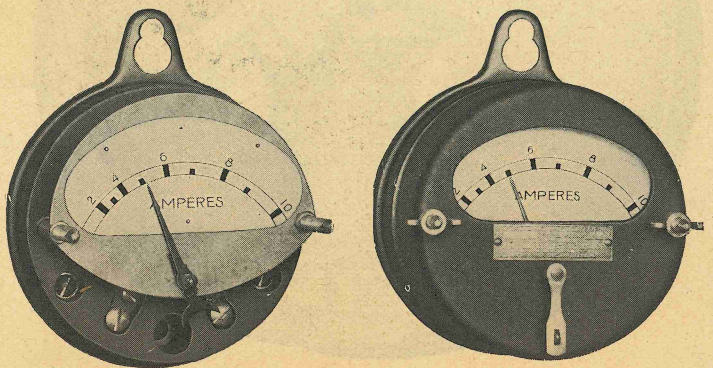

Figure 18—Type H. Maximum Demand Meter—General Electric Co.

This device, like the preceding, is not a true watt indicator, but can be calibrated the same as the Wright.

The Printometer. The Printometer is a printing watt-hour meter, that is at certain intervals, say every 15 minutes, a reading of the instrument is printed on a tape. The difference between successive readings gives the kilowatt-hours used during the interval. If this number is divided by the time interval the result will be the average power demand, in kilowatts, for that interval.

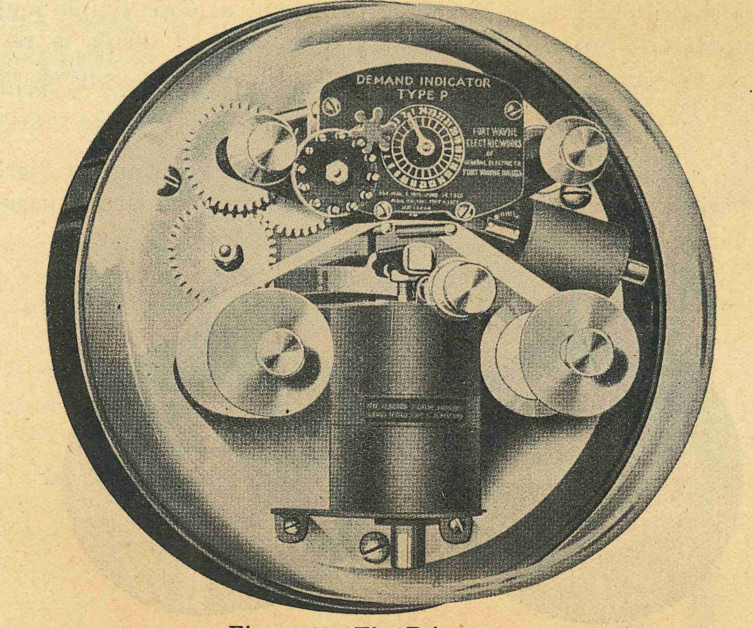
DEMAND INDICATOR
TYPE P
FORT WAYNE
ELECTRIC WORKS

Figure 19—The Printometer

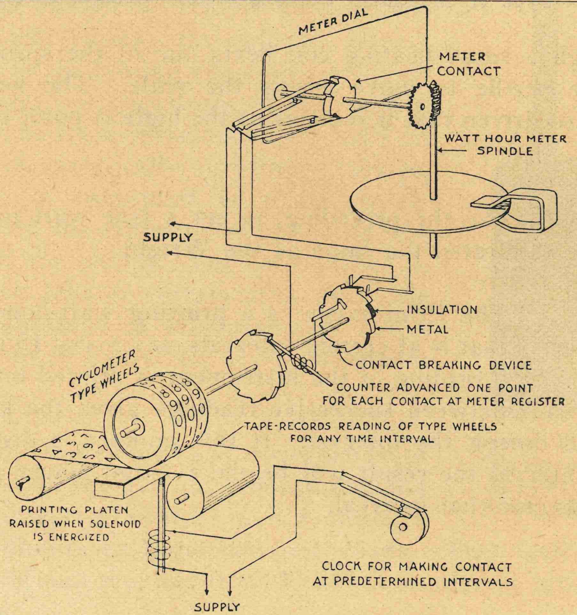
METER DIAL
METER CONTACT
WATT HOUR METER SPINDLE
SUPPLY
INSULATION
METAL
CONTACT BREAKING DEVICE
COUNTER ADVANCED ONE POINT FOR EACH CONTACT AT METER REGISTER
CYCLOMETER TYPE WHEELS
TAPE-RECORDS READING OF TYPE WHEELS FOR ANY TIME INTERVAL
PRINTING PLATEN RAISED WHEN SOLENOID IS ENERGIZED
CLOCK FOR MAKING CONTACT AT PREDETERMINED INTERVALS
SUPPLY

Figure 20—Complete Diagram of the Printometer

Figures 19 and 20 illustrate this device. The type wheels are notched up by an electri-magnet connected to a contact device attached to the watt-hour meter, while the printing mechanism is actuated by an electro-magnet, connected to a contact device on small motor, or a clock. If the printometer is to be used on an a-c. circuit, a small synchronous motor operates the timing device, while if it is for a d-c. circuit the clock is used. The timing device can be made to print the reading at any desired interval, such as five, ten, fifteen, thirty minutes or one hour.

Conclusion. The student will realize that the subject of measurement of power is a large subject and a thorough understanding of it can be had only by much study and experience in power measurement work. The first step is the mastery of the principles set forth in this and other lessons of this course.

DEMONSTRATION FOR LESSON IX.

1. Measure the current and voltage supplied to an electric iron connected to a d-c. circuit and calculate the watts consumed. Express the power also in horse power.

2. Use a wattmeter to measure the power delivered to the electric iron.

3. If an alternating-current circuit is available show that, where the load is inductive, as with a motor, the product of amperes and volts does not equal the reading of the wattmeter. Calculate the power factor.

4. If possible demonstrate the two-wattmeter method of three-phase power measurement.

QUESTIONS.

1. A direct-current motor takes 35 amperes at 220 volts.
   (a) Find the watts input.
   (b) Find the horse-power input.

2. Why is it necessary to use a wattmeter to determine the power in most alternating current circuits? Explain fully.

3. A single-phase motor takes 25 amperes at 220 volts and a wattmeter in the circuit reads 4500 watts.
   (a) What is the apparent power?
   (b) What is the Power factor?

4. Explain how the power is determined for a two-phase, four-wire circuit.

5. What is the two-wattmeter method of measuring power? Explain briefly.

REFERENCE BOOKS.

Electricity Experimentally and Practically Applied; by Sidney W. Ashe—D. Van Nostrand Co., New York.

Applied Electricity for Practical Men; by Arthur J. Rowland—McGraw-Hill Book Co., New York.

Elements of Electricity and Magnetism; by Franklin and McNutt—McMillan Co., New York.

Elements of Electricity; by Timbie—McMillan Co., New York.

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Alternating Currents; by George T. Hanchett—John Wiley & Sons, New York.

INDEX.

Page

Combination of Instruments 18
Definition of Power 3
Maximum Demand Meters 20
Polyphase Wattmeters 18
Power, Definition of 3
Power in a Direct-Current Circuit 5
Power in a Simple Alternating-Current Circuit 7
Power in a Two-Phase Circuit 8
Power Rating 4
Printometer, The 23
Three-Phase Delta Connected Circuit 13
Three-Phase Star Connected Circuit 9
Two-Wattmeter Method 16
Type H. Demand Meter 23
Voltage, Current and Power in a Three-Phase Star Connected Circuit 9
Wattmeter, Curve Drawing 20
Wright Maximum Demand Meter 21

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LESSON IX : : : MEASUREMENT OF POWER

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